NASA CR-72072
PWA-2897

FOURTH QUARTERLY REPORT

BRAYTON-CYCLE TURBOMACHINERY ROLLING-ELEMENT BEARING SYSTEM

prepared for
National Aeronautics and Space Administration

August 1966

Contract NAS3-7635

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio
Lloyd W. Ream

Prepared by H Means H. Means, Project Engineer

Approved by Peter Bolan P. Bolan, Program Manager

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD, CONNECTICUT

#30

FOREWORD

This report describes the progress of the work conducted between April 2 and July 2, 1966 by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut, on Contract NAS3-7635, Brayton-Cycle Turbomachinery Roller-Contact Bearings, for the Lewis Research Center of the National Aeronautics and Space Administration. The objective of the program is to design and demonstrate performance of a rolling-element bearing system for the Brayton-cycle turbomachinery being developed under Contracts NAS3-4179 and NAS3-6013.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

I. SUMMARY

This report discusses the work completed during the fourth three-month period of a design and experimental program formulated to investigate the potential of an oil-lubricated rolling-element bearing system for Brayton-cycle space power machinery. The technical progress, the work accomplished and the program status for the fourth quarterly period, April 2 through July 2, 1966, are presented.

During the previous report periods, the rolling-element bearing lubrication system was analyzed and the designs of the turbine-compressor and turboalternator on rolling-element bearings were completed. The experimental apparatus which will be used to investigate the features of the lubrication system were also completed and fabrication of these test rigs was initiated. During this report period fabrication of the experimental rigs proceeded. Also, a 600-hour test of a candidate adsorber configuration was conducted. The permissible level of oil contamination in the primary Brayton-cycle fluid was reviewed.

II. INTRODUCTION

In the application of the Brayton cycle to space power sources, two types of rotor support systems are being considered and evaluated by the National Aeronautics and Space Administration. In one case, the rotating components are supported by gas bearings and the cycle working fluid is used as lubricant and bearing coolant. In the other case, the rotors are supported by rolling-element bearings which are lubricated and cooled by oil.

The specific Brayton-cycle machinery considered in this program consists of a turbine-driven compressor and a turbine-driven alternator. These units are being developed utilizing gas bearings under Contracts NAS3-4179 and NAS3-6013. The gas bearing version of this machinery is shown in Figure 1. The cycle flow enters the compressor at 76°F through the inlet duct around the housing which contains a thrust bearing and a radial bearing. The argon is compressed in the six-stage axial-flow compressor and then flows through the radial diffuser exit scroll and ducting. The argon is heated to 1490°F outside of the unit and is returned to the turbine inlet ducting and scroll. A second radial gas bearing is located between the compressor exit and turbine inlet. The argon flows through the single-stage axial-flow turbine which drives the compressor at 50,000 rpm. It then exhausts through the exit ducting which connects to the two-stage alternator-drive turbine. The 4-pole alternator is driven at 12,000 rpm and is supported by bearings on each side. After passing through the alternator-drive turbine, the argon exhausts through the exit scroll and ducting. It is cooled outside of the machinery and returned to the compressor inlet.

The vast majority of Brayton-cycle powerplants in use in the world today employ rolling-contact oil-lubricated bearings. In the application of Brayton-cycle machinery to the space environment, several significant questions require investigation to determine if rolling-element bearings can provide a satisfactory rotor support system for this application:

1) Can rolling-element bearings provide the endurance capability with the high reliability required in space applications for a nominal mission time of 10,000 hours?

2) Can the lubricant be cooled and circulated in a zero-gravity environment?

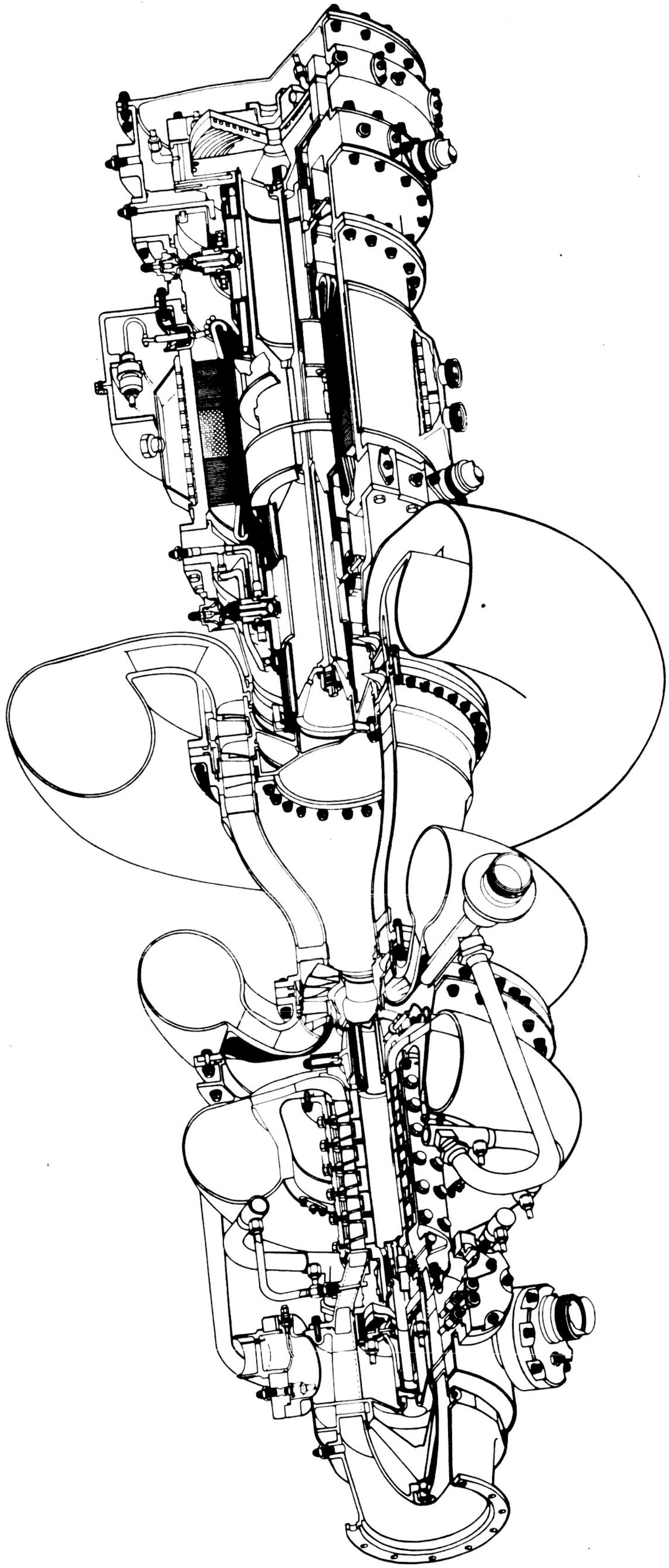


Figure 1 Brayton-Cycle Turbomachinery Employing Gas Bearings (Contracts NAS3-4179 and NAS3-6013)

3) Can the lubricant system and bearing cavities be sealed with low parasitic power losses by components with the required life capability?

4) Can the lubricant be prevented from contaminating the cycle working fluid (argon)?

The purpose of this program is to design and investigate the performance of a rolling-element bearing system for the turbine-compressor and turboalternator being developed under Contracts NAS3-4179 and NAS3-6013. The components of this rolling-element bearing system are bearings, seals, lubrication system and gas cleanup system. The work consists of the following four phases:

1) Design of a rolling-element bearing system that retains components of the turbine-compressor and turboalternator (designed under Contracts NAS3-4179 and NAS3-6013) to as great an extent as practical with no alteration in aerodynamic design. The shaft support system is intended to achieve low parasitic losses commensurate with high reliability for the full mission life.

2) Design and fabrication of component test rigs.

3) Conduct bearing, seal, scavenge, separator, and adsorber performance tests.

4) Conduct a pilot endurance demonstration of the rolling-element bearing system.

Although the rolling-element bearing system encompasses the turboalternator as well as the turbine-compressor, only the rolling-element bearing system components for the turbine-compressor are investigated experimentally. The separator, which is an integral part of the turboalternator, is evaluated in a separarate test rig as is the residual oil adsorber.

The designs of the rolling-element bearing system and of the component test rigs in Phases 1 and 2 were completed during the previous report periods[1, 2, 3]. 100-hour adsorber performance tests were performed and fabrication of the other component test rigs was initiated during the previous report periods. This report presents a summary of the activity during the fourth quarter which concentrated on rig fabrication and a long-time adsorber test.

---

1 Numbered references are listed in Appendix 1

III. BEARING-SEAL-SCAVENGE RIG

The performance of selected components of the oil-lubricated rolling-element bearing system will be evaluated experimentally. Turbine-compressor components were selected for experimental evaluation because they were considered to be more critical than similar elements in the turboalternator. Since the turbine-compressor bearings, seals, and scavenge pumps are about the same size and located adjacent to each other, one basic test rig was planned in order to test each component separately or in combination. Two versions of the bearing-seal-scavenge test rig have been designed: a seal test rig and a bearing-scavenge rig. The bearing-scavenge rig can also incorporate a seal for certain tests.

The seal test rig design is presented in Figure 2. The shaft is driven by an air turbine (not shown in Figure 2) and the central portion of the rig contains jet oil lubricated bearings which support the shaft. The test seal is mounted on the outboard end of the shaft to provide a dead-end leakage cavity. Since the only source of oil in the cavity is leakage past the test seal, the performance of the test seal can be accurately assessed. In order to cool the seal, oil is introduced in the turbine drive end of the shaft and flows through an annular passage and then through the rotating sealplate.

During this report period, the fabrication of the seal test rig proceeded and approximately 87 percent of the parts were completed. These parts are shown in Figure 3 and certain individual parts are presented in Figures 4 through 8. Figures 5 and 6 are photographs of the initial seal planned for evaluation. This is a carbon face seal with a welded bellows secondary seal intended to be operated without lubricant in the contact area between the carbon and the rotating plate. The various seal designs considered for experimental evaluation were discussed in the previous quarterly report[3].

The bearing-scavenge rig design is presented in Figure 9. This design is a duplicate of the arrangement at one end of the turbine-compressor. Oil and oil-argon mist are introduced at the free end of the shaft and pass through the bearing and scavenge pump in the same way as in the turbine-compressor. The seal can be included in this arrangement if desired. The housing on the test end of the rig and the shaft are, of necessity, not the same as the corresponding part of the seal version of the rig. The drive turbine and rig bearing area employ the same parts as are used in the seal rig.

The fabrication of the bearing-scavenge test rig continued during this report period and approximately 60 per cent of the parts were completed.

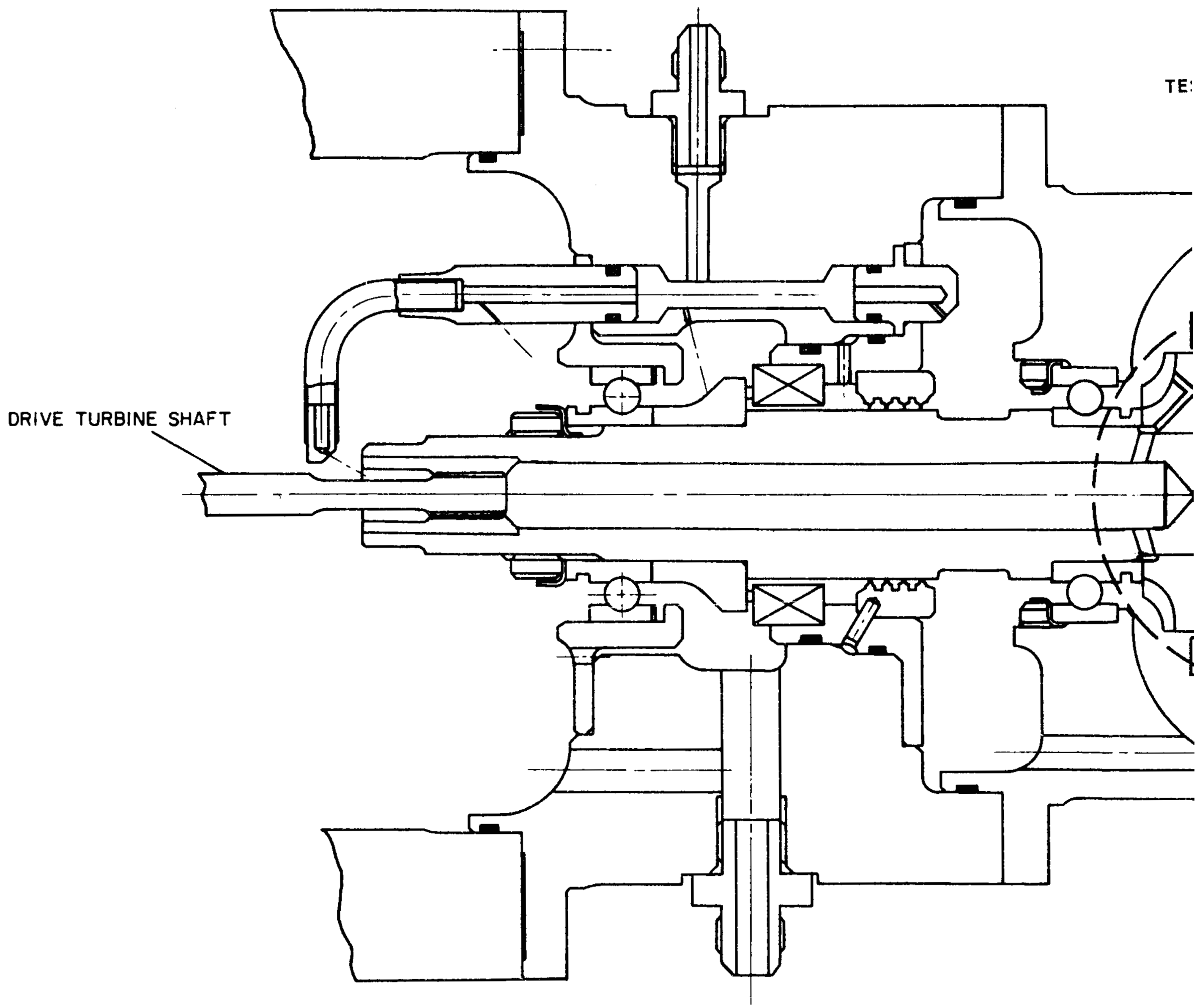
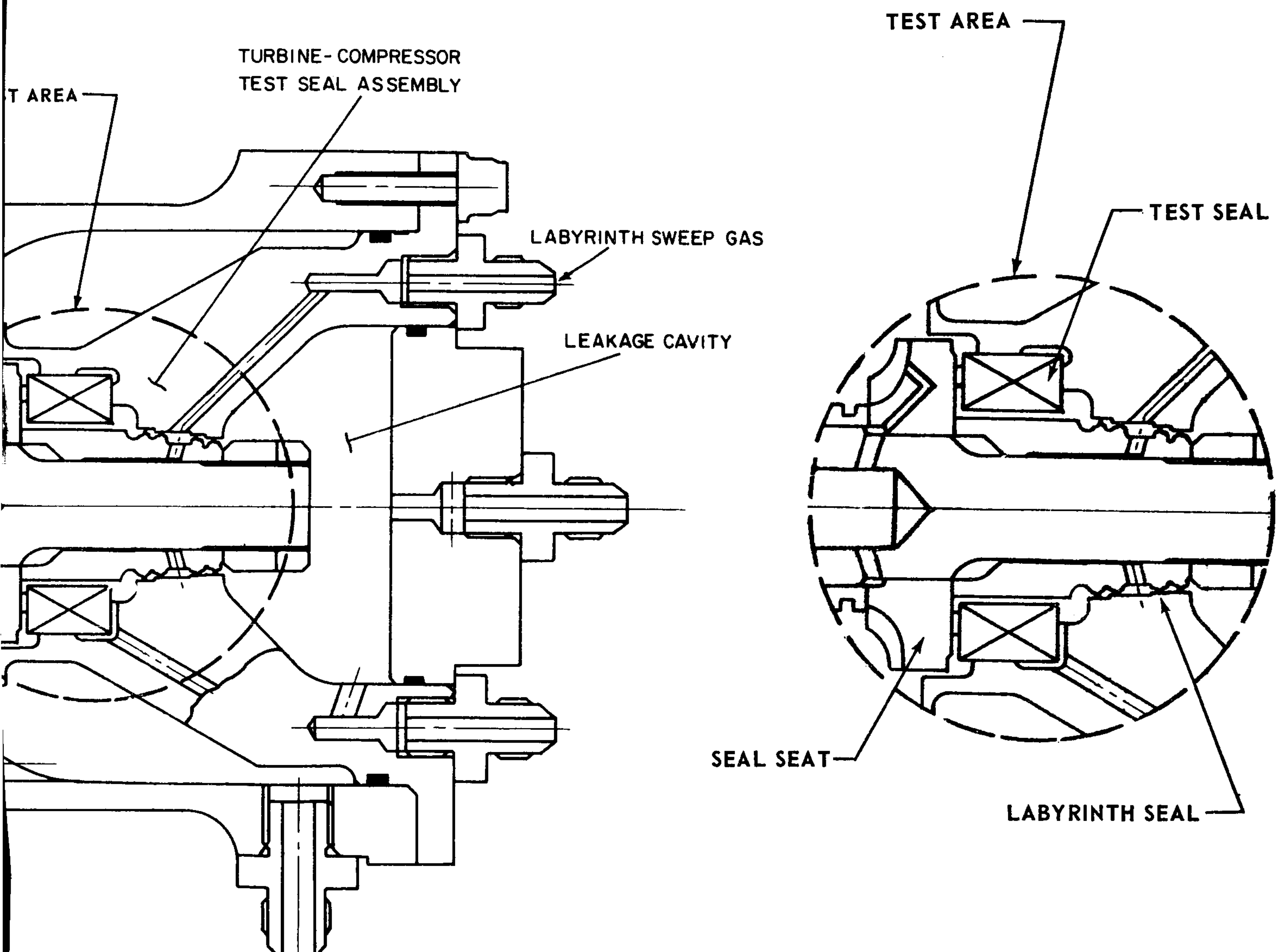


Figure 2 Turbine-Compressor Seal Test Rig


T AREA
TURBINE-COMPRESSOR
TEST SEAL ASSEMBLY
LABYRINTH SWEEP GAS
LEAKAGE CAVITY
TEST AREA
TEST SEAL
SEAL SEAT
LABYRINTH SEAL

6. 2

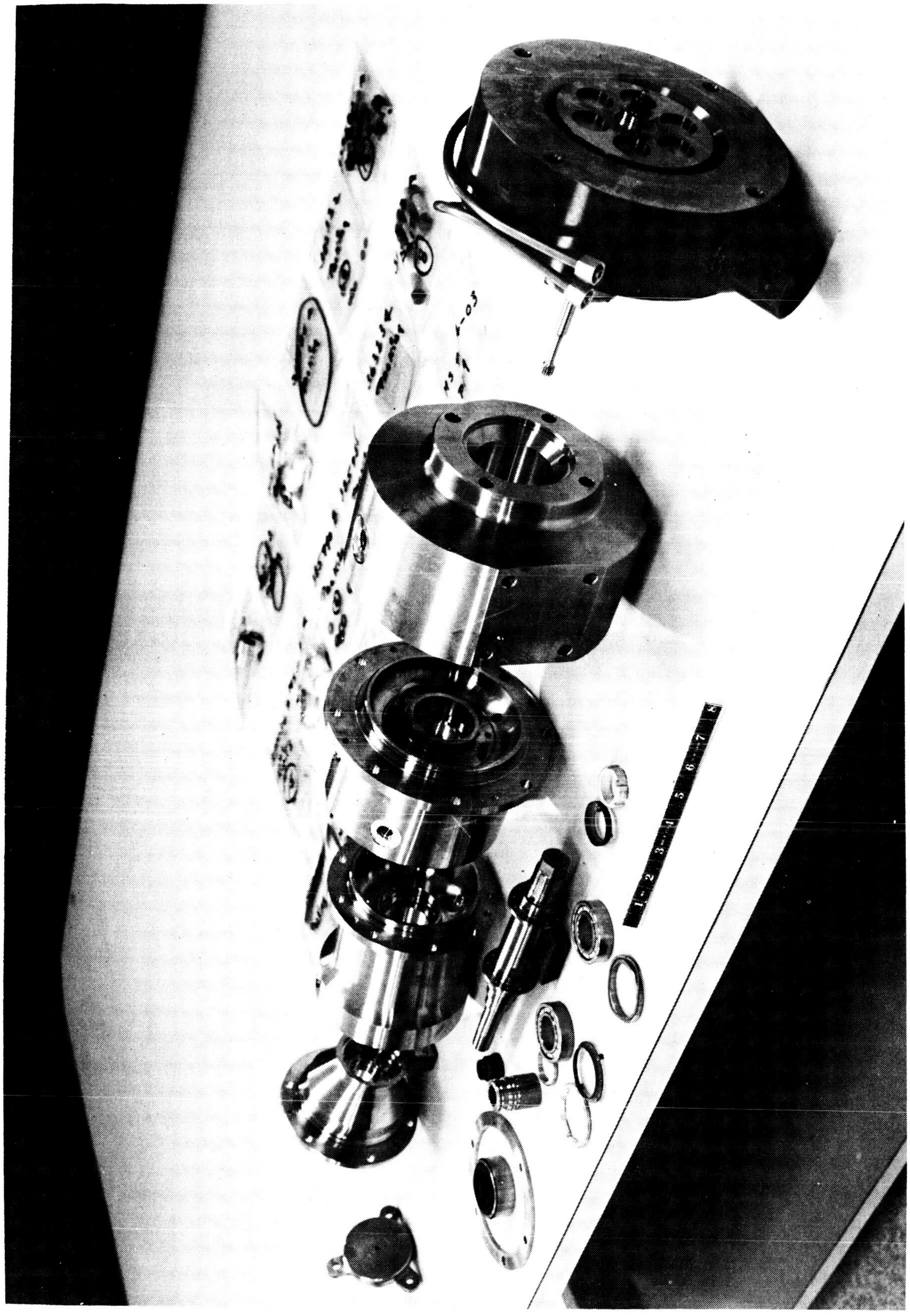


Figure 3 Seal Test Rig Parts X-22339

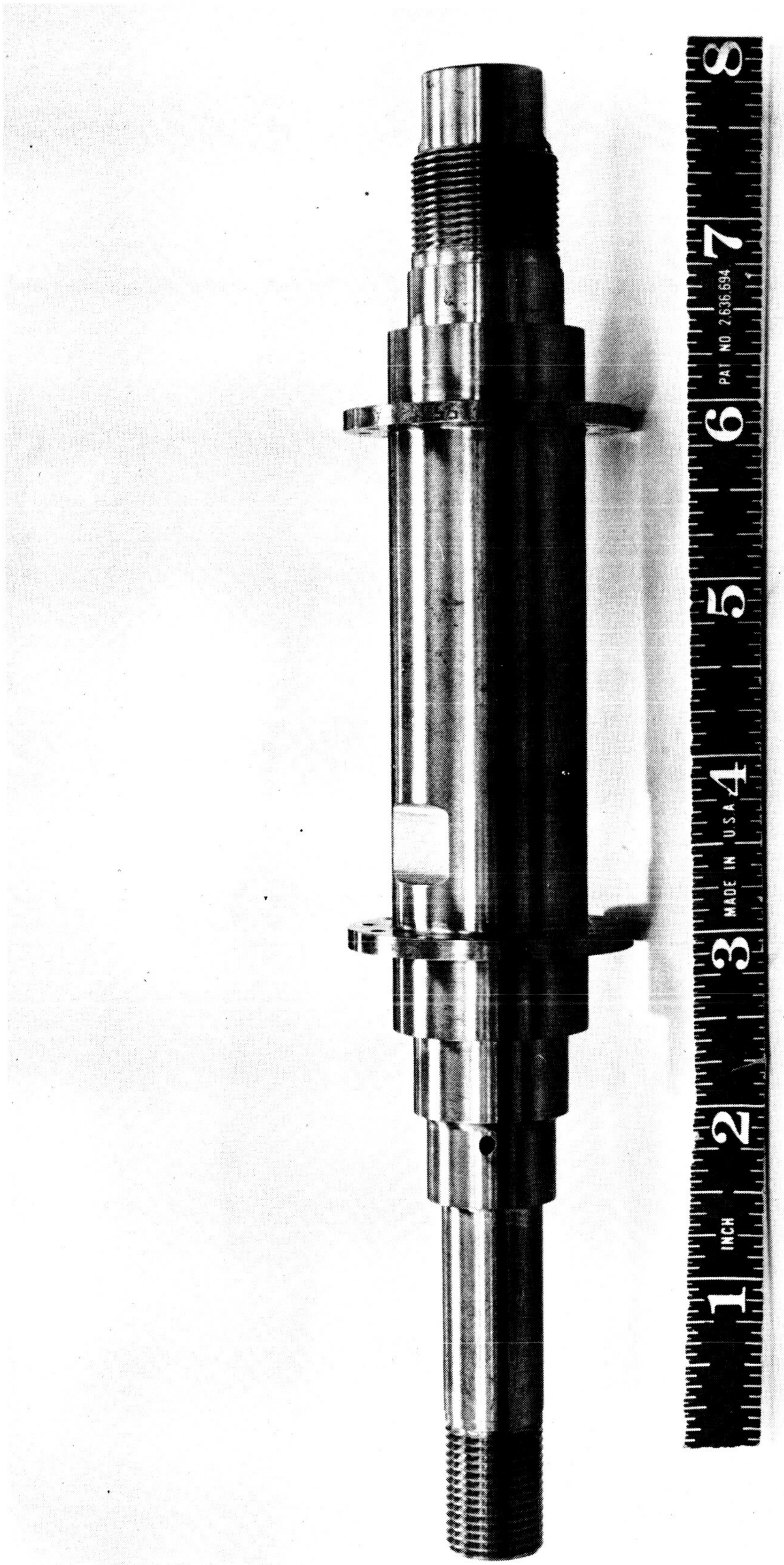


Figure 4 Shaft - Seal Test Rig X-22340

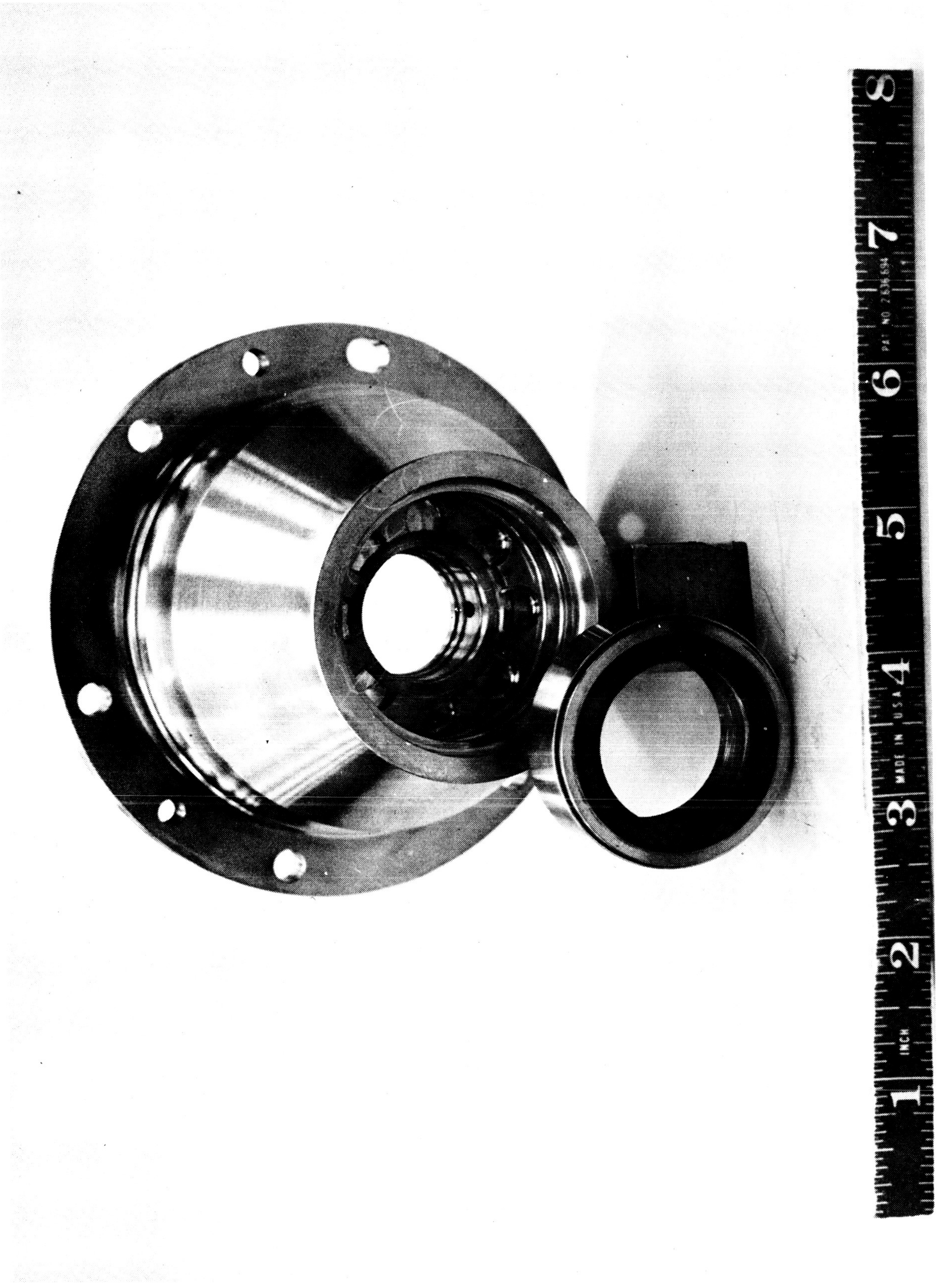


Figure 5 Seal and Seal Housing - Seal Test Rig X-22338

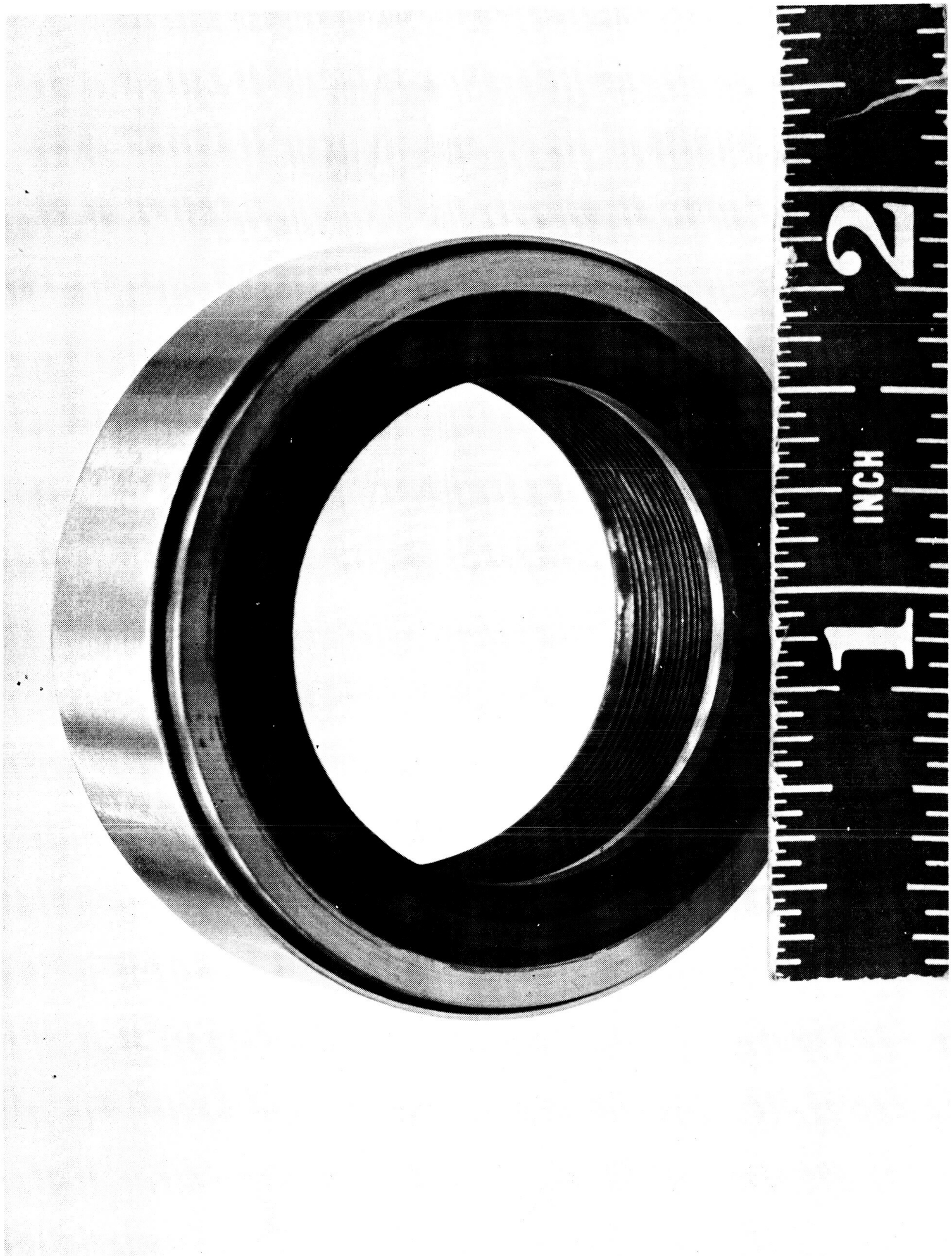


Figure 6 Face Seal - Seal Test Rig X-22341

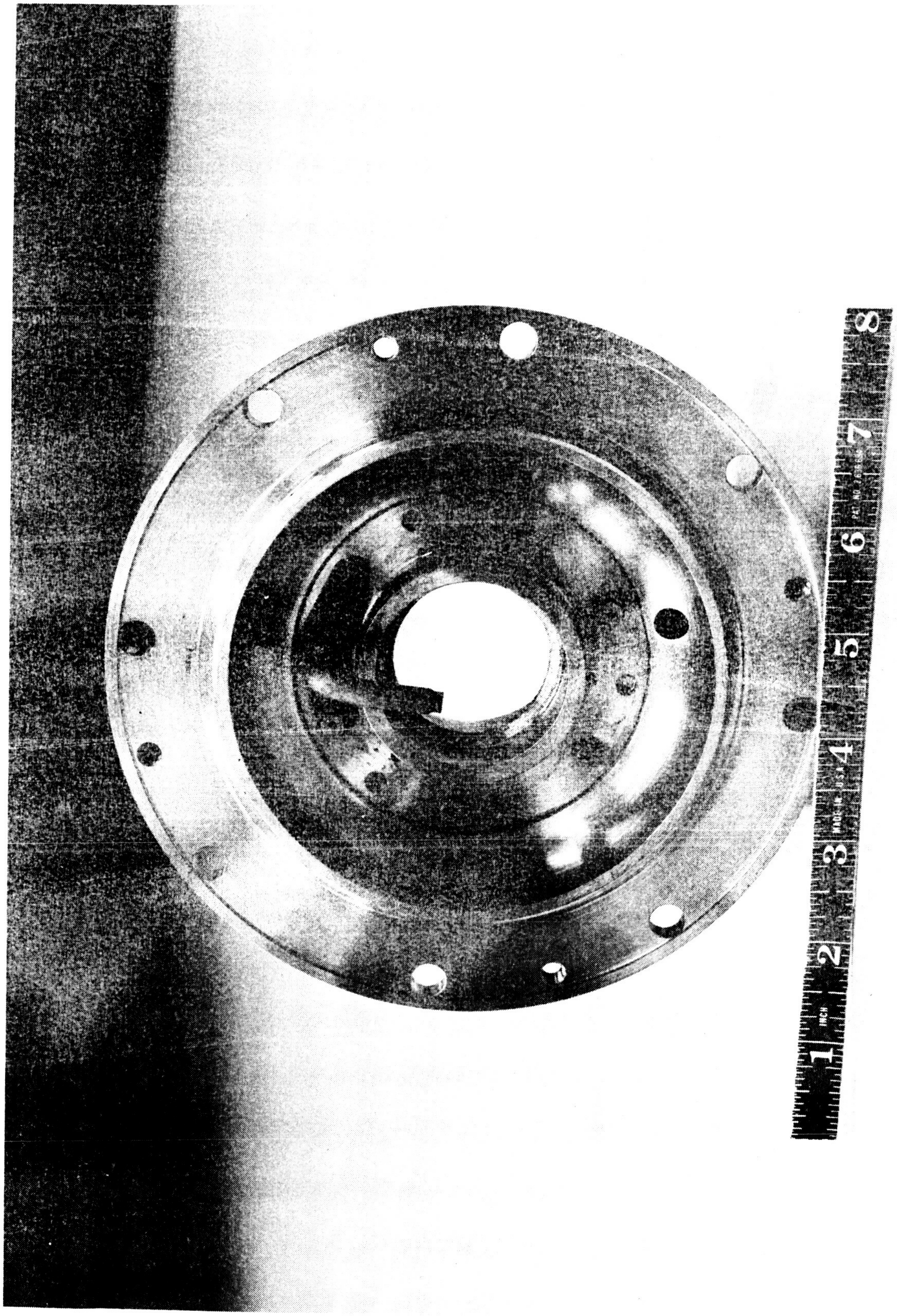


Figure 7 Intermediate Housing - Seal Test Rig X-22343

Figure 8 Drive Turbine - Seal Test Rig X-22344

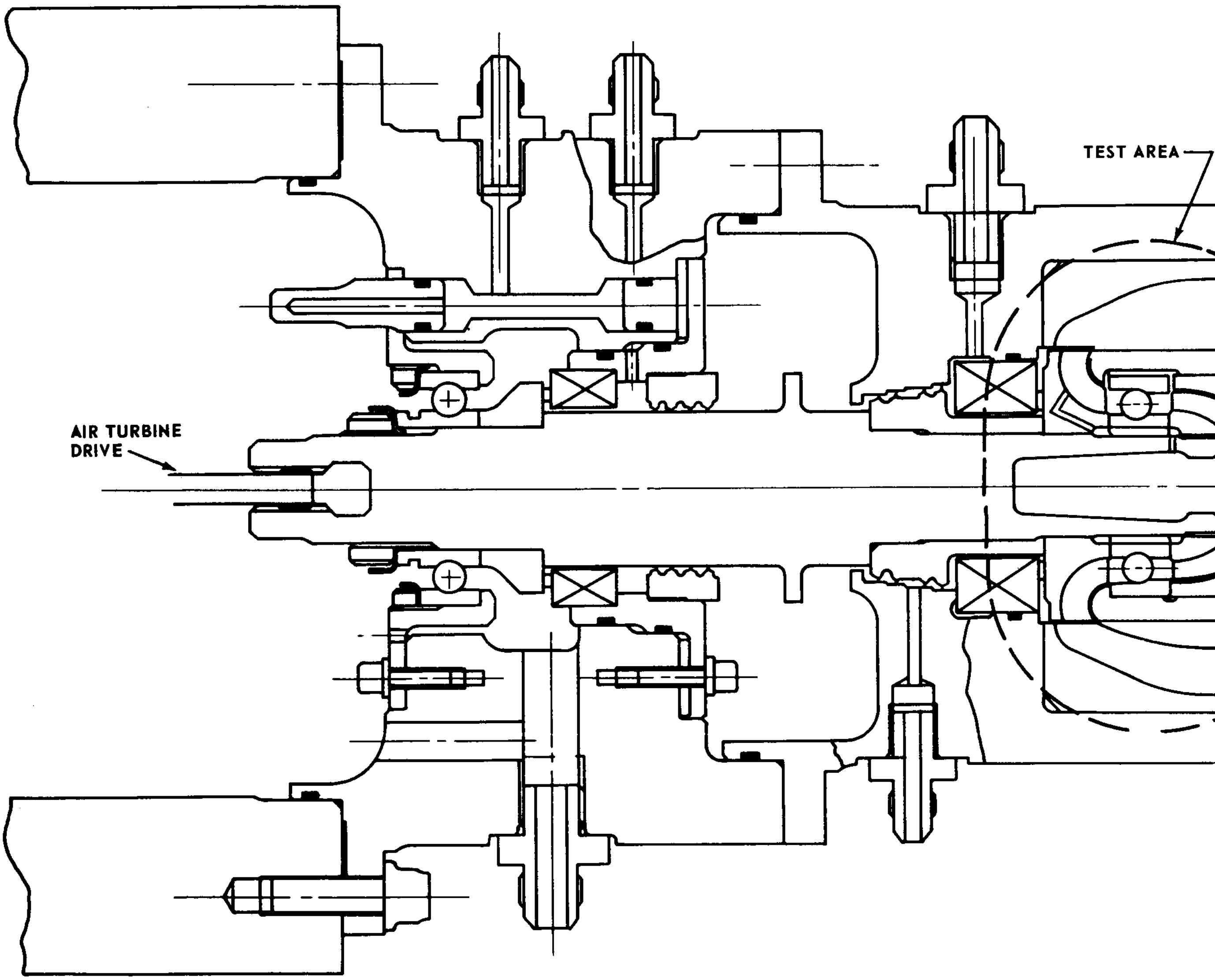
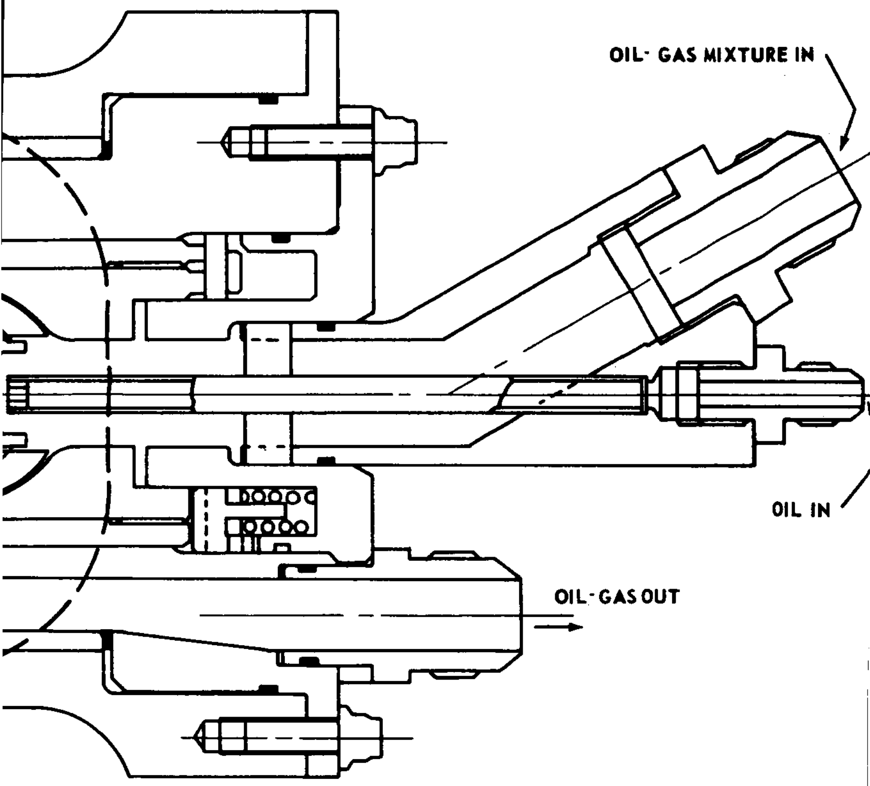
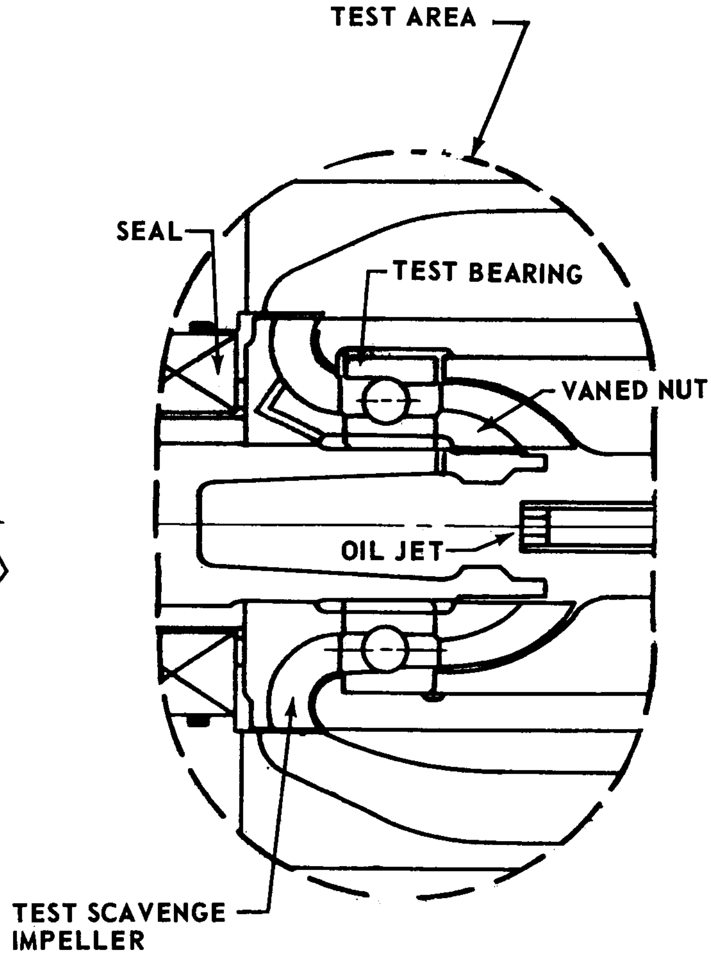


Figure 9 Turbine-Compressor Bearing-Scavenge Rig



13 (2)


TEST AREA
SEAL
TEST BEARING
VANED NUT
OIL JET
TEST SCAVENGE
IMPELLER

13 3

IV. SEPARATOR-PUMP RIG

The oil-gas separator and oil pump are two components, in addition to the turbine-compressor bearing, seal, and scavenge components, which have been selected for experimental investigation. Both components are mounted on the free end of the turboalternator and operate at 12,000 rpm.

The separator-pump test rig has been designed to evaluate pump performance, separator performance, and combined pump-separator performance. The general arrangement of the separator-pump test rig, presented in Figure 10, is similar to that of the bearing, seal, and scavenge test rigs. The rig is driven by an air turbine and the test components are overhung from an intermediate housing. The rig configuration presented in Figure 10 combines a scoop pump and a separator section. Initial separation will be accomplished at the scoop pump where the bearing compartment scavenge gas-oil mixture is introduced, filling the shaft reservoir with oil. Oil is pumped from the shaft reservoir to the accumulator by the scoop pump and the gas, oil vapor and overflow oil flow into the separator. In the separator the oil and gas are separated by centrifugal forces. The separated oil is pumped along the sloping outer wall and discharged forward towards the bearing compartment, while the argon is discharged from the rear of the separator and is piped out of the compartment. The test rig is designed to evaluate pump and separator designs individually as well as simultaneously.

During the previous report period, the design of the separator-pump rig was completed and detail manufacturing drawings were produced. Raw materials for the rig parts were procured. During this report period, fabrication of the separator-pump rig proceeded and approximately 30 per cent of the parts were completed.

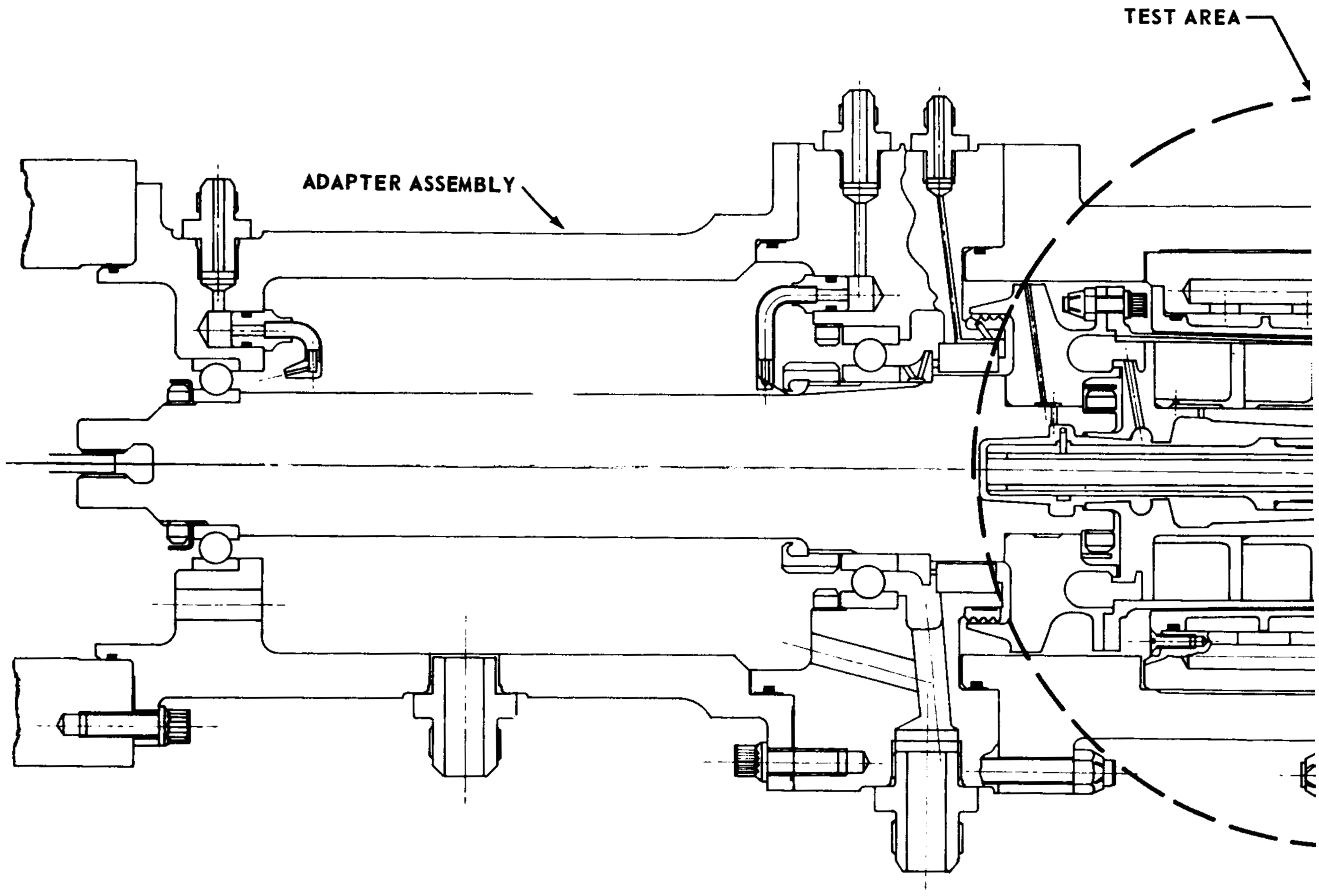
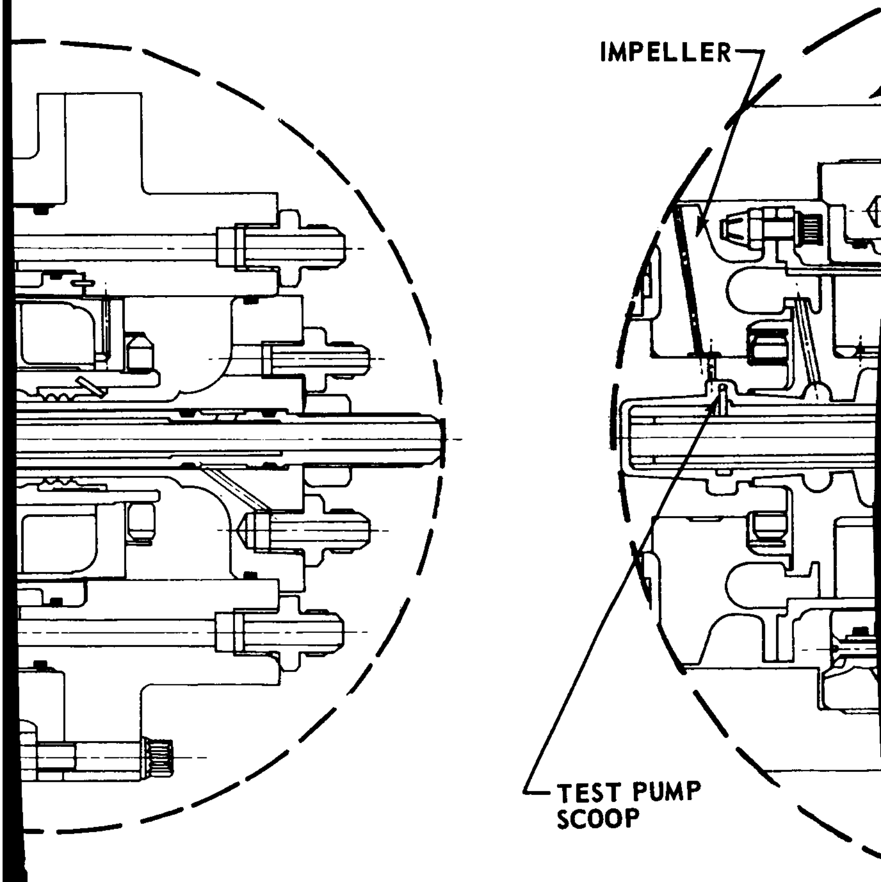


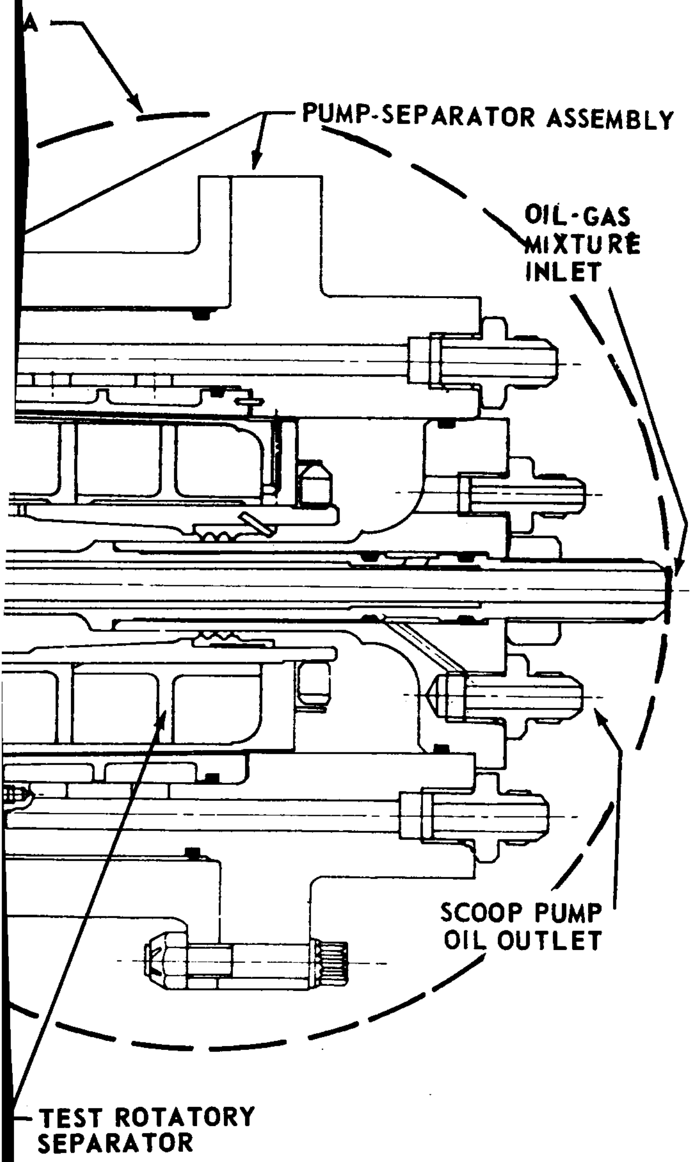
Figure 10 Turboalternator Pump-Separator Rig

0

TEST ARE



15 (2)


A
PUMP-SEPARATOR ASSEMBLY
OIL-GAS
MIXTURE
INLET
SCOOP PUMP
OIL OUTLET
TEST ROTATORY
SEPARATOR

15 (3)

V. ADSORBER PROGRAM

The lubricant for the rolling-element bearings must be segregated from the high-purity main Brayton-cycle argon system. The design concept being pursued under this contract utilizes a combination of face seals and labyrinth seals to accomplish this separation. Some argon will leak through the face seals into the the bearing compartments and this bleed argon must be returned to the main cycle. To prevent contamination of the primary cycle gas, the returning leakage gas must be purified. Oil in the form of droplets will be removed from the gas in a centrifugal separator which will also cool the gas to reduce the oil vapor partial pressure. Final purification of the argon will be accomplished by passing the gas through an adsorber bed prior to returning it to the main cycle at the compressor inlet. Primary emphasis has been placed on the use of molecular sieve materials in the adsorber bed for removal of lubricant from argon. The molecular sieve materials are alkali metal aluminosilicates which have been conditioned by removal of the water of hydration.

As reported previously[1, 2, 3], an adsorber test rig was constructed to evaluate molecular sieve materials for this application. The test rig consisted of a vaporizer, a swirl separator, and an adsorber column. Argon was bubbled through heated oil in the vaporizer to produce a mixture containing argon, oil vapor, and entrained oil. The gas-oil mixture leaving the separator was cooled to 100°F, corresponding to system adsorber inlet design temperature. This cooling caused precipitation of finely-divided oil particles in the gas stream which remained suspended in the stream. The gas stream passed through a swirl separator prior to entering the adsorber test section to remove entrained oil droplets. This separator simulated the function of the centrifugal separator attached to the turboalternator. After leaving the separator, the gas stream containing some oil particles and oil vapor passed through the adsorber column. Adsorption evaluation tests of Linde 4A and 13X molecular sieve materials were made in a series of 100-hour tests. Also, pressure drop data were developed for the powder and pellet forms of the adsorber materials.

As reported previously [2, 3], both materials removed essentially all of the oil entering the adsorber bed and the Linde 13X material appeared somewhat superior. The pellet form of this material was not as efficient as the powder form in adsorption per unit weight but the pellet form offers much lower pressure drop characteristics. Therefore, Linde 13X pellets were chosen for a long-time test of the adsorber design concept. The endurance goal in this test was 1000 hours. The adsorber bed was designed to operate with the same flow per unit area as might be used in a full-size unit with an apparent argon velocity of 14 feet per minute. The length of a full-scale adsorber bed with Linde 13X pellets would be of the order of 100 inches with a pressure drop of about 0.25 psi. For the long-time test a bed length of 30 inches was selected since the goal was a 1000-hour test.

The adsorber endurance test rig, Figure 11, is similar in basic concept to the rig employed in the 100-hour test, except that certain features were incorporated to allow greater operating and control capability than was available with the 100-hour test rig. Dual manifold vaporizers and swirl separators were included in the rig so that these units could be serviced without interrupting the test. In each of the parallel lines, larger size swirl separators (Norgren Type 12-002) were used to accommodate the increased oil transport. A Pyrex glass tube, 32 inches long by 1.31 inches in inside diameter, was selected for the adsorber column. It was equipped with manometer fittings at locations 1.5, 16.5 and 31.5 inches from the inlet. A manometer fitting was placed in the inlet tube.

Inside the Pyrex glass tube, the adsorber column consisted of a zone of approximately 1.5 inch of loosely packed glass wool (1.0156 grams), encasing a Teflon stand and a 30-inch zone of Linde 13X molecular sieve pellets. The pellets are 1/8-inch long by 1/16-inch diameter. A glass wool plug (0.07 grams) was placed in the 1/4-inch tube at the exit. Glass wool was included at each end of the adsorber bed to retain the pellets and to aid in the flow distribution.

Downstream from the adsorber, the rig was equipped with two parallel-connected molecular sieve scrubber columns intended to collect all of the oil leaving the test adsorber. At 100-hour intervals during the test, one scrubber was removed and its contents measured while the argon flow was directed through the other scrubber. A total hydrocarbon analyzer was installed to monitor the argon from the test adsorber column on a programmed schedule of one minute every hour for the duration of the test. Thus, it was intended to detect minor oil discharge at 100-hour intervals and comparatively large oil discharge at one-hour intervals. Argon gas flow rate through the rig was indicated by a calibrated wet test meter located after the scrubber columns.

Materials used for this test were carefully controlled. The argon gas contained less than 20 ppm total reactive impurities which were predominantly water and oxygen in typical cylinders analyzed. The lubricant consisted primarily of a five-ring polyphenyl ether mixture along with small amounts of four-ring compounds and an additive. The lubricant was preconditioned by bubbling argon at 350°F for a minimum of 48 hours to remove volatiles. The molecular sieve pellets were heated in air at 575°F for a period of 72 hours to desorb CO_2 and water vapor and thereafter were stored in a dry atmosphere.

Operating conditions for the endurance test were chosen to correspond to conditions anticipated in the Brayton-cycle machinery. These conditions are similar to the situation in the 100-hour tests. The argon flow rate of 3.6 liters per minute in the 1.31-inch diameter column corresponds to the mass flow rate

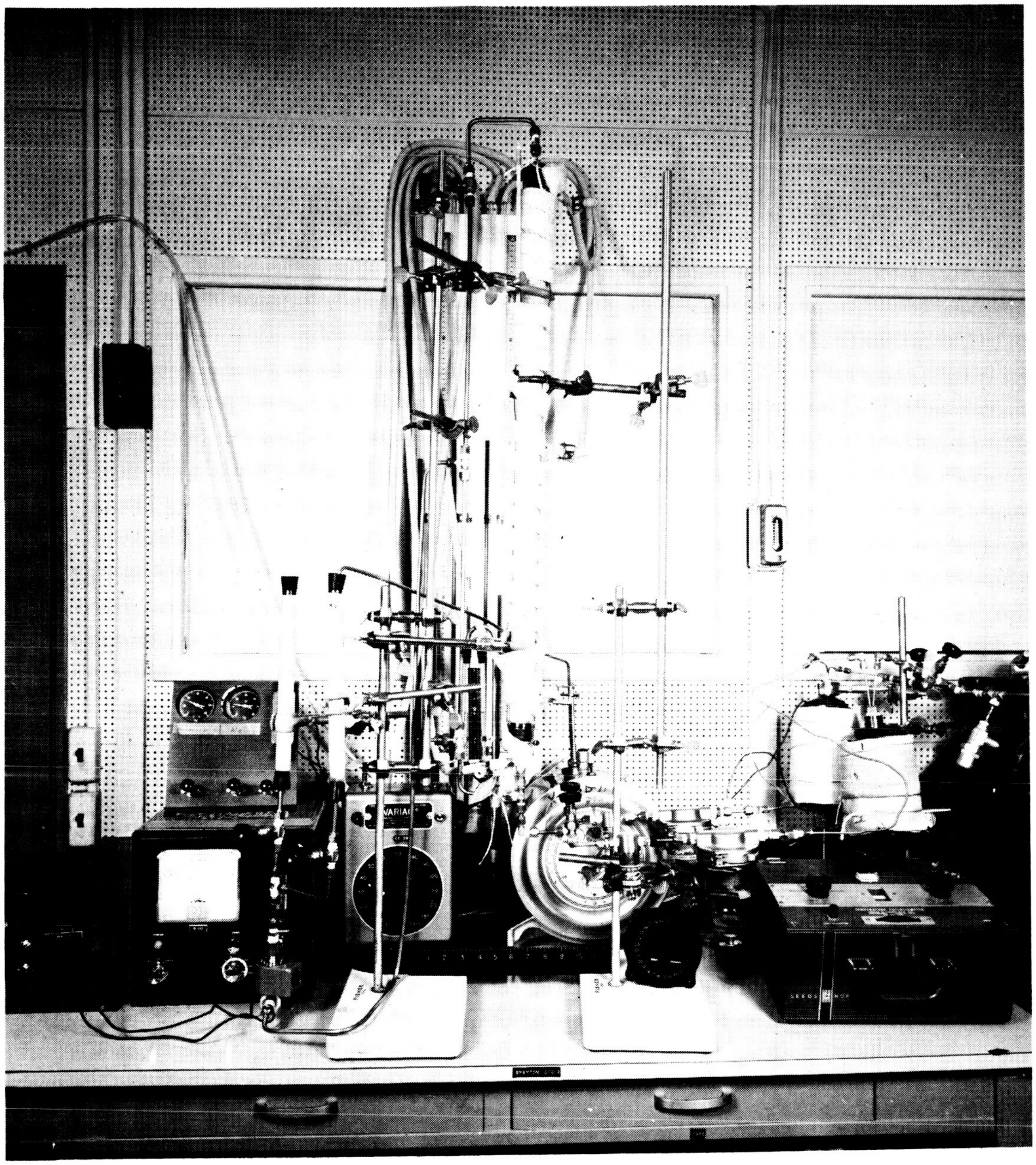


Figure 11 Apparatus for Long-Time Adsorber Test H-58136

per unit cross-sectional area of 1.1 liter per minute flow in the 0.742-inch inner diameter columns in the 100-hour tests. Vaporizer temperature was maintained at 350°F and the adsorber column temperature 100°F. Oil concentration in the argon gas stream was subject to variation because of physical effects. The nominal mass transport rate averaged about 1 gram of oil per liter of argon in 100 hours.

The scrubber column was removed at 100-hour intervals and replaced with a new scrubber column containing new adsorber material. After removal, the contents of the scrubber column were analyzed by constant temperature chromatography. The total content of the column was immersed in benzene, extracted, and boiled down to 1 ml samples for chromatographic analysis.

The adsorber endurance test rig was operated at the selected conditions for a total of 600 hours. Evidence of oil collecting in the glass wool packing at the column inlet was observed and the oil accumulation in this case continued to increase with test time. It extended almost completely around the tube when the test was terminated as shown in Figures 12 and 13. Some adsorber pellets adjacent to this zone showed a brown coloration similar to that of pellets saturated with lubricant in previous saturation capacity tests. Pressure measurements were taken every 24 hours at the four locations on the column and the results are presented in Figure 14. The pressure drop across the whole adsorber including the glass wool increased about 0.04 psi. This pressure loss occurred primarily across the glass wool and can be attributed to the increase in resistance due to the oil collecting in the glass wool.

Visual inspection of the Pyrex glass container indicated the formation of a very thin film on the inner wall at the top of the adsorber bed. Figure 16 shows the film after 600 hours, when a swab sample of the film was identified as lubricant.

For the duration of the test, the hydrocarbon content of argon discharged from the adsorber column was monitored by means of a total hydrocarbon analyzer one minute out of every hour. All results indicated that the discharged argon contained less than 3 microliters of oil per liter of argon. Analysis of a standard methane gas mixture at regular periods throughout the test period verified that instrument calibration and response were satisfactory.

The test was interrupted at 500 hours when the pressure measurements suggested a flow resistance in the exit plumbing. Also, some pellets at the exit of the adsorber bed showed a brown color which is indicative of oil saturation of the pellets (the pellets are normally white). The first discoloration was observed

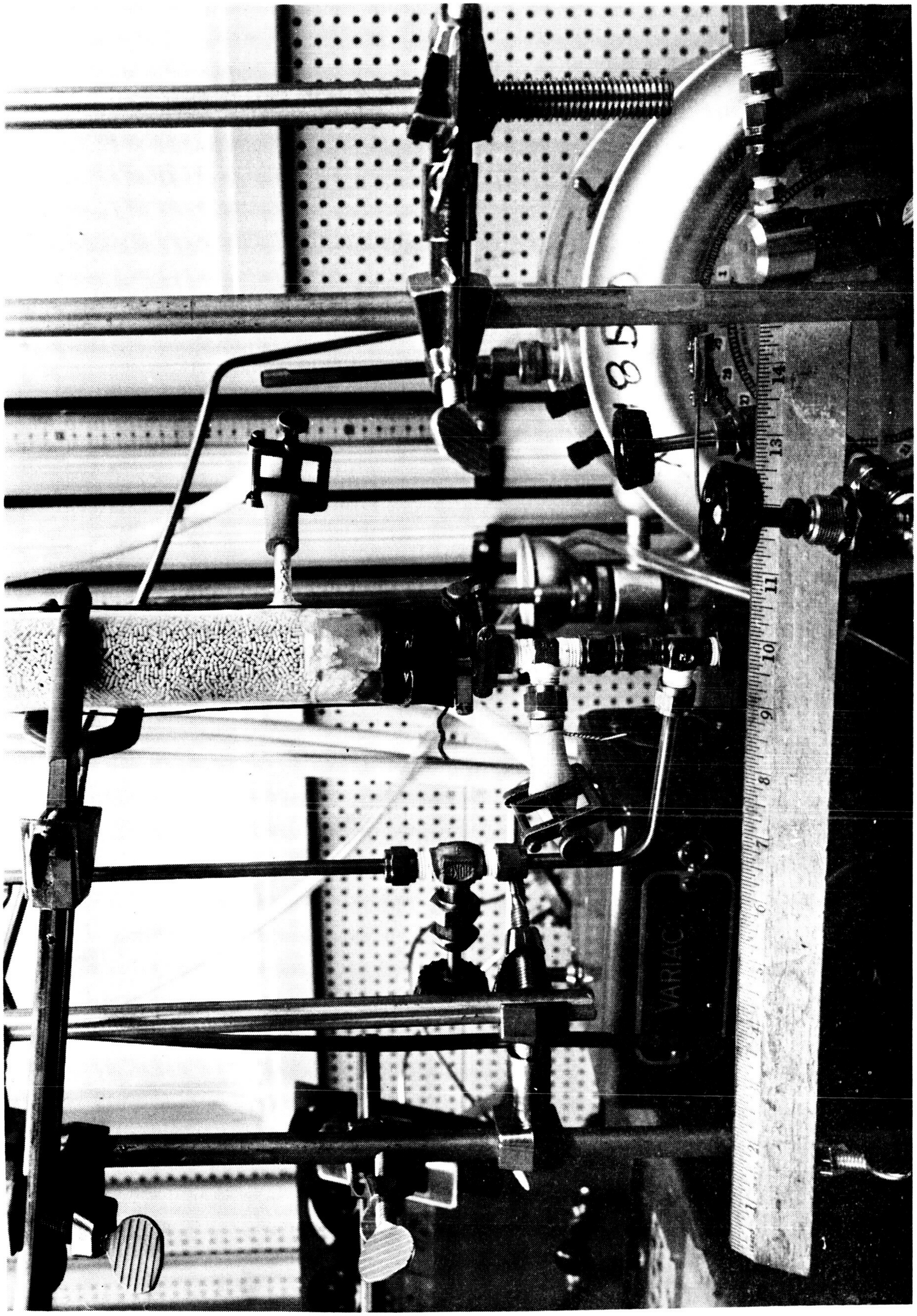


Figure 12 Inlet Section of Adsorber Column at 370 Hours H-58570

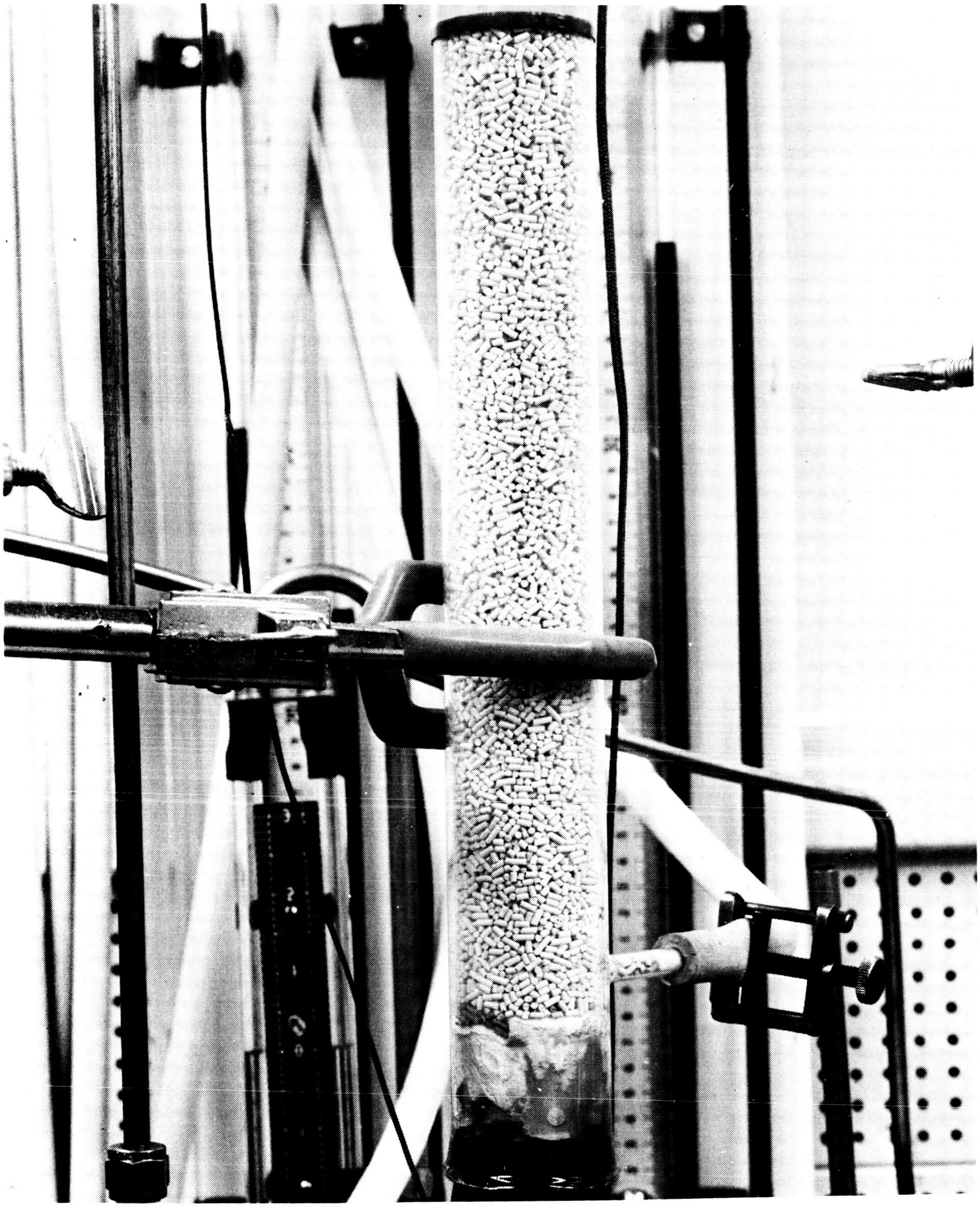


Figure 13 Closeup of Adsorber Inlet Section at 600 Hours H-58784

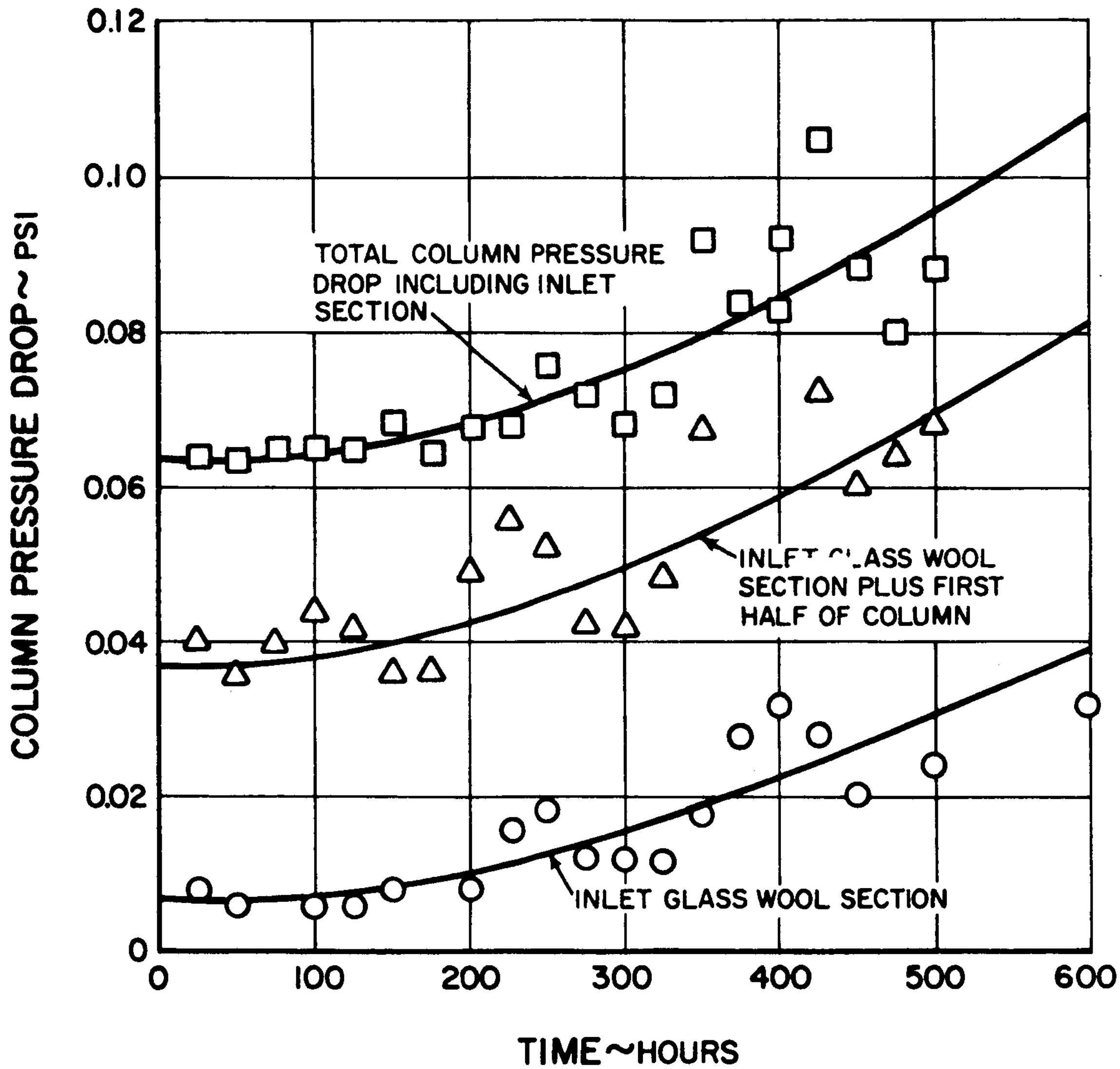


Figure 14 Pressure Drop Characteristics of Adsorber Column

after 370 hours of operation. The exit tubing was removed and the glass wool located at the exit of the bed was found to contain a significant quantity of oil, 0.46 gram. Visual observation of this oil accumulation was not possible since the glass wool was located in the metal tube at the exit. The top layer of pellets was removed and the discolored pellets were analyzed and found to contain 0.367 gram of oil per gram of pellets. This concentration indicates that the discolored pellets were saturated with oil. No discolored pellets were observed in the adsorber bed except at the inlet and exit ends where pellets were in contact with the glass wool.

Although precautions were taken to thoroughly clean the exit tubing prior to the test, the possibility of oil contamination due to improper cleaning could not be completely eliminated. Therefore, the exit tubing was removed, cleaned, and reassembled. A clean glass wool packing was installed and the test was restarted.

The scrubber at the exit of the rig was analyzed to determine the quantity of oil in the discharge argon. 0.014 gram of oil accumulated in the scrubber in the 100 hours prior to the interruption at 500 hours, indicating a small breakthrough. Figure 15 presents a plot of the total oil that entered the rig and the total oil leaving the adsorber. The breakthrough of a small amount of oil between 400 and 500 hours is evident in this figure. The oil flow entering the rig was determined by periodically bypassing the adsorber and measuring the oil content of the flow out of the swirl separator in the total hydrocarbon analyzer. This measurement is subject to some error. The measurement of the oil leaving the adsorber was a result of measuring the contents of the scrubber beds. The confidence in this measurement is relatively high.

While the scrubber contents were being analyzed, the adsorber test was continued to 600 hours with the new glass wool in the exit section. The adsorber bed was not disturbed during the interruption at 500 hours, except to remove a small layer of pellets from the top of the bed as shown in Figure 16. At 600 hours the test was interrupted again and the glass wool in the exit section was examined and found to contain 0.075 gram of oil. This oil was collected between 500 and 600 hours. No oil was detected in the exit tubing which had been cleaned at 500 hours when the new exit glass wool was installed. At the 600-hour point, the contents of the scrubber used between 400 and 500 hours had been analyzed and the small oil breakthrough shown on Figure 15 was found. Therefore, the test was terminated at 600 hours to permit analysis of the oil content in the adsorber bed and the inlet glass wool section.

The glass wool packing at the inlet of the adsorber bed contained 13.20 grams of oil located primarily near the outer diameter. This constituted the majority of

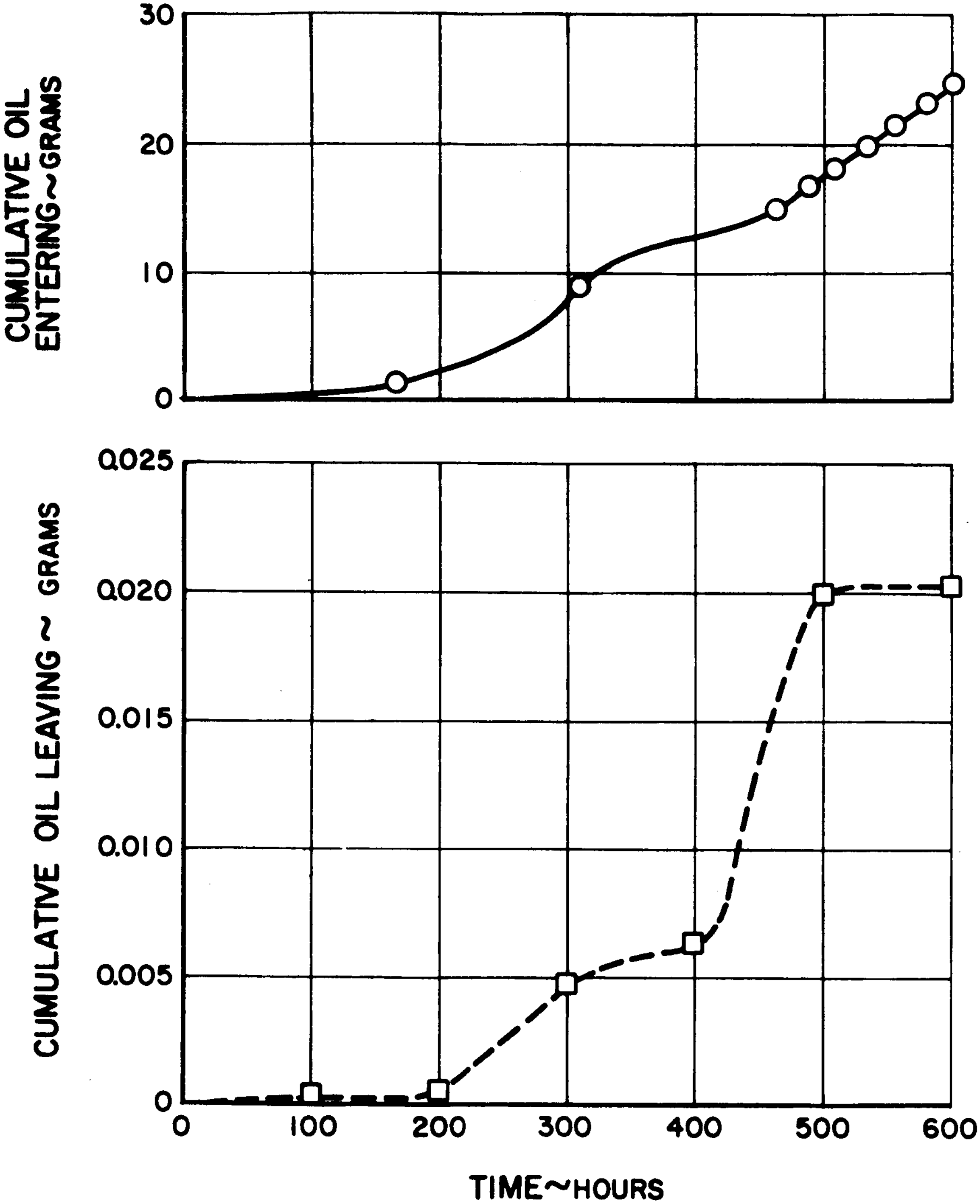


Figure 15 Cumulative Oil Flow in Long-Time Adsorber Endurance Test

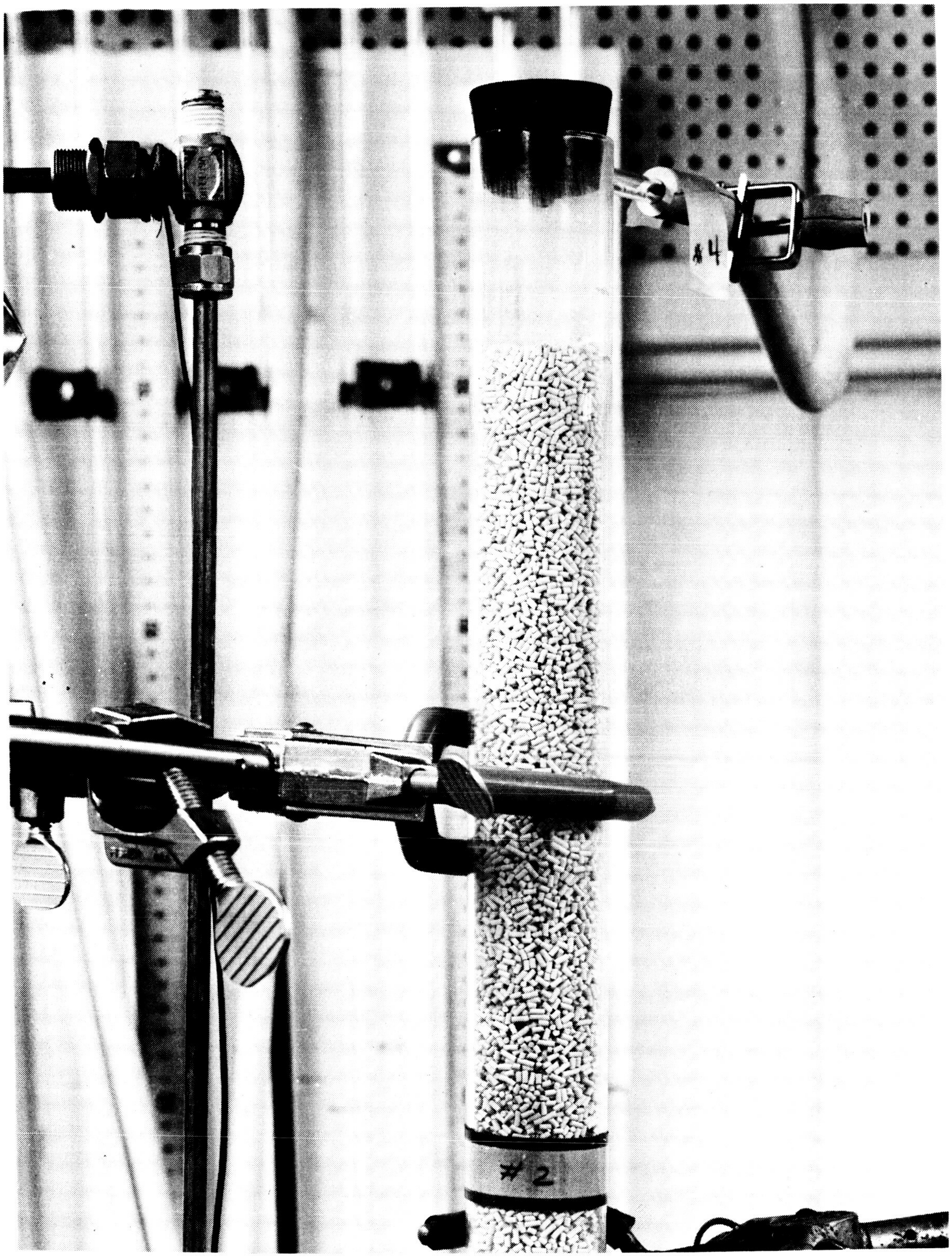


Figure 16 Exit End of Adsorber Column at 600 Hours H-58783

the oil entering the adsorber. The inlet tubing between the separators and the adsorber contained 3.30 grams of oil which could have run back from the inlet glass wool section. The exhaust scrubber used between 500 and 600 hours contained 0.0002 gram of oil.

The oil content in the adsorber bed was measured and a total of 0.5856 gram was found. The Linde 13X pellets were removed in approximately 1/2-inch layers near the inlet of the column and in 1-inch layers for the remainder of the tower. The oil content of each layer was determined using the chromatograph. Also the weight of each layer of pellets was determined. The oil distribution measured in the adsorber bed is presented in Figure 17. As this figure indicates, the bulk of the oil adsorbed in the bed is contained in the first inch of material. 90.3 per cent (0.5285 gram) of the oil was contained in the first 1.06 inch of the bed. The inlet section contained small pellets that were discolored, indicating saturation. The normal saturation level determined previously is 0.3305 gram of oil per gram of pellets. Some of the saturated pellets are visible in Figure 13. These pellets appear to be in contact with the glass wool and may have acquired oil by wicking. The bulk of the bed adsorbed 0.0001 to 0.0002 gram of oil per gram of adsorber, and this level is fairly constant throughout the length of the bed. This result was not expected since the concentration of oil is decreasing as the oil-gas mixture proceeds through the column. A decreasing amount of oil adsorbed might be expected. The 100-hour test indicates such a reduction. The results of the 100-hour test with Linde 13X pellets are also presented on Figure 17. The column length of the 100-hour test was 10 inches. Evidently the first inch or two of the column produced essentially the same performance in both the 100-hour and 600-hour tests. Apparently the 100-hour test was not of long enough duration to show a low level of adsorption for the bulk of the column as was found in the 600-hour test.

A second unexpected result in comparing the 100-hour test with the 600-hour test is the fact that the first inch or so of the bed did not adsorb more oil in the long term test than in the short. Since the adsorption level is approximately one order of magnitude less than saturation, the longer test was expected to adsorb more oil as a result of the longer exposure. Actually, the oil adsorption in the long and short tests are quite similar as shown in Figure 17.

The third unexpected result was the oil breakthrough. In the 100-hour test, benzene scrubbers were employed and no oil was detected downstream of the adsorber. In the 600-hour test a total of 0.0202 gram of oil was found in the exit scrubbers. Also, 0.6269 gram total was found in the exit glass wool, exit stopper and exit tube in the 600 hours of testing. While the quantity of oil trans-

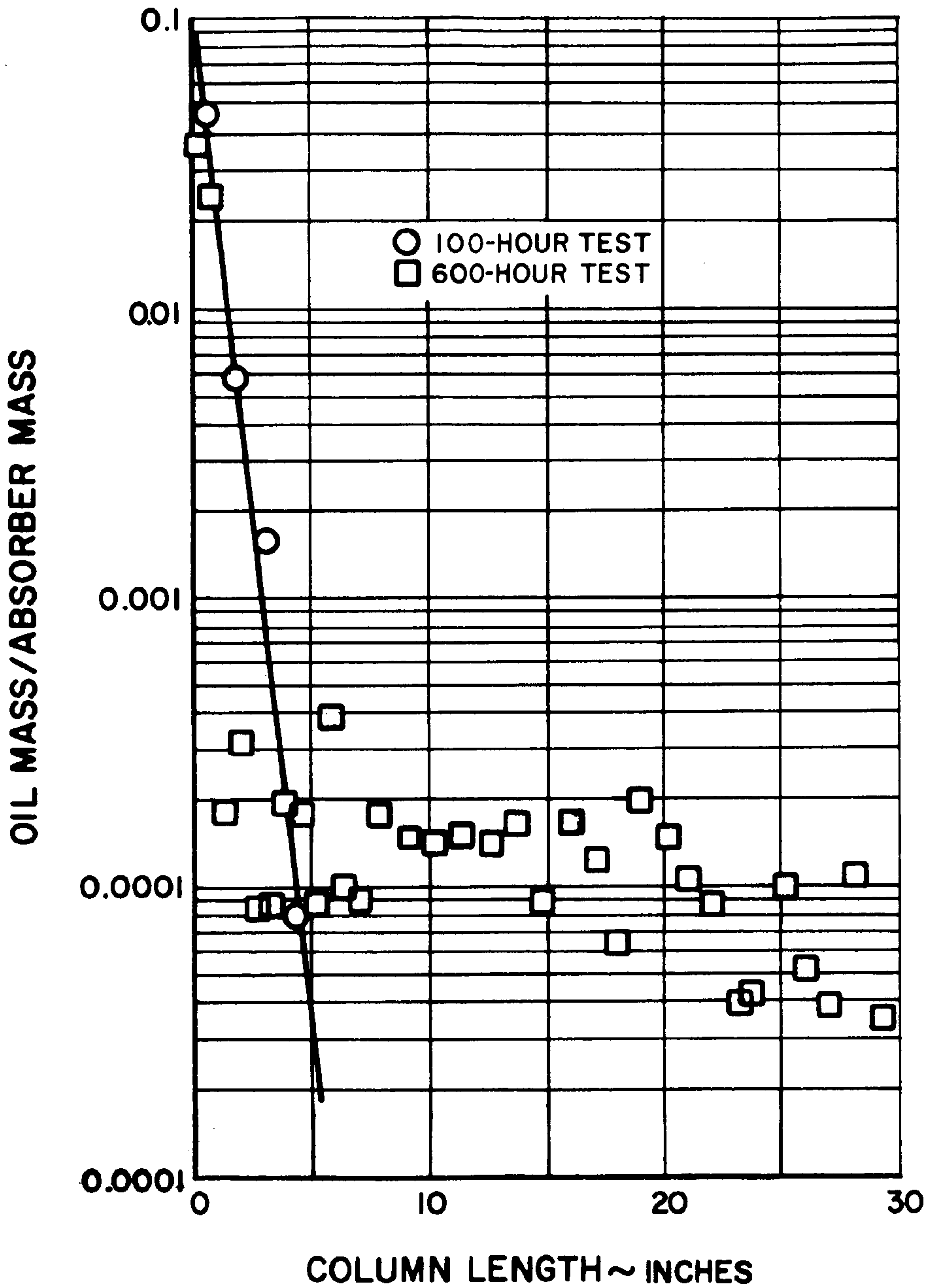


Figure 17 Adsorber Performance. Linde 13X Pellets

mitted through the column is small it is roughly the same magnitude as the oil adsorbed in the pellets. Evidently, the Linde 13X pellets are not adsorbing the combination oil vapor and aerosol which is leaving the glass wool as effectively as desired.

Some other mechanism of oil transport through the bed may be of importance. The length of the adsorber column and the previous tests indicate that channeling is not a factor. Capillary action may be a factor, however. Capillary activity which might not be of importance in 100 hours could be a factor for extended periods such as 600 hours. A very thin film was observed on the glass wall at the top of the column, which may be seen in Figure 16. A swab of this film was analyzed and found to contain oil. No capillary barrier was included in the bed design. A capillary or non-wetting barrier should be considered in the design of the adsorber.

A major discovery in the 600-hour test is the effectiveness of the glass wool in collecting the aerosol. The glass wool cannot adsorb oil vapor but oil droplets can be entrained in the wool. A test was conducted to determine the potential saturation of the glass wool by immersing glass wool in oil and measuring the weight of the glass wool before and after immersion. The wool contained oil amounting to 27.2 times it own weight. The tentative conclusion from the 600-hour test is that the adsorber should be designed with a combination of glass wool to collect the oil particles and Linde 13X molecular sieve material to act as a blotter to hold the oil particles by wicking, and to adsorb the oil vapor.

VI. LUBRICANT CONTAMINATION INVESTIGATION

Some small amount of oil will weep past the seals or migrate through the adsorber and enter the primary cycle. In order to establish the maximum quantity of oil contamination that can be allowed for a 10,000-hour mission, an investigation of the consequences of oil contamination was undertaken. This study involved three basic areas:

1) Identification of the products formed by pyrolysis (thermal decomposition) of the lubricant.

2) The distribution or location where the various products of the pyrolysis will accumulate in the system.

3) The consequences to powerplant performance from oil pyrolysis products in certain locations leading to the fouling of heat transfer surfaces, blockage of flow passages, and introduction of gases into the argon.

A previous quarterly report[1] described the results of the first two parts of the investigation and presented incomplete results of the third. This report presents further results concerning the consequences of introducing gaseous products of oil decomposition, particularly hydrogen, in the basic cycle fluid, argon. A brief summary of the previous results is also included.

The identification of the products produced by pyrolysis of the lubricant is restricted by the limited data available at the conditions encountered in the Brayton cycle. However, polyphenyl ethers can be expected to form tar containing carbon and polymer and to evolve a small quantity of gases. Solid products may be expected to build up in the hotter areas, such as at the heater where the highest temperature exists and therefore where rapid pyrolysis reaction rates will occur. Some of the gaseous products formed may be adsorbed in the molecular sieve (adsorber in the oil separation system). Of course, these products must first leak through the seals before passing through the adsorber. Gaseous hydrogen will accumulate in the cycle fluid unless special precautions are introduced to prevent such an accumulation. There is a possibility that some low-volatility liquid products may condense in the cooler parts of the system.

Deposition of coke or tar in the heater will reduce system performance due to the increase in flow resistance. If the Brayton-cycle efficiency were reduced approximately 1.5 per cent which corresponds to an increase in $\Delta P/P$ of approximately 0.02 and if the material were deposited fairly uniformly, the system would be able to absorb something over 5 pounds of oil in the course of the mission. The effect of such deposits on heat transfer coefficients is relatively small because the thermal resistance of the gas film is fairly high.

The release of hydrogen gas as a result of oil pyrolysis appears to be the factor limiting the allowable Brayton cycle oil contamination. The preliminary investigation reported previously indicated that roughly 0.05 pound of oil in the system may be limiting if special precautions are not employed. Therefore, a more extensive investigation was conducted to evaluate the effects of hydrogen contamination in the primary cycle assuming a variety of conditions.

The Brayton-cycle system was analyzed with various amount of hydrogen gas added to a nominal inventory of 0.331 pound of argon. The thermodynamic properties of the mixtures of argon and hydrogen, presented in Figure 18, were used in the evaluation of cycle performance. As the gas properties vary, the performance of the various components of the powerplant also vary, and the variations in the performance of the cooler, compressor, regenerator, heater and turbines were included. Compressor inlet temperature was assumed constant.

Two of the types of heat sources being considered for application with the Brayton-cycle machinery are solar energy and isotope decay. With the solar heat source in an earth orbit, the solar energy is concentrated on a heat receiver which contains heat storage material. Energy is stored by melting the storage material and is extracted as the material freezes. Since the melting temperature of the storage material is constant, this type of energy source is sometimes assumed to provide a constant turbine inlet temperature over a limited range. Therefore, the performance of the Brayton-cycle system with hydrogen addition and constant turbine inlet temperature was analyzed, and the results are presented in Figure 19.

As hydrogen gas is added to the cycle as a result of oil pyrolysis, the pressure level in the cycle is increased and the specific heat of the gas mixture is increased. Since, for this study the compressor inlet temperature is assumed constant and turbine inlet temperature is artifically held constant, the power output is increased as the hydrogen gas is added. The increase in power output is a result of the increased specific heat of the mixture and the increase in mass flow. However, the turbine-compressor speed also increases. It reaches 20 per cent overspeed with 0.0065 pound of hydrogen. The turbine-compressor was designed to be able to operate at 20 per cent overspeed for moderate periods. Since the maximum contamination occurs at the end of the life of the powerplant, the 20 per cent overspeed condition can be considered a limit. At this condition the power produced is increased by approximately 70 percent of the rated power, which exceeds the rating of the alternator (15 KVA at 0.8 power factor).

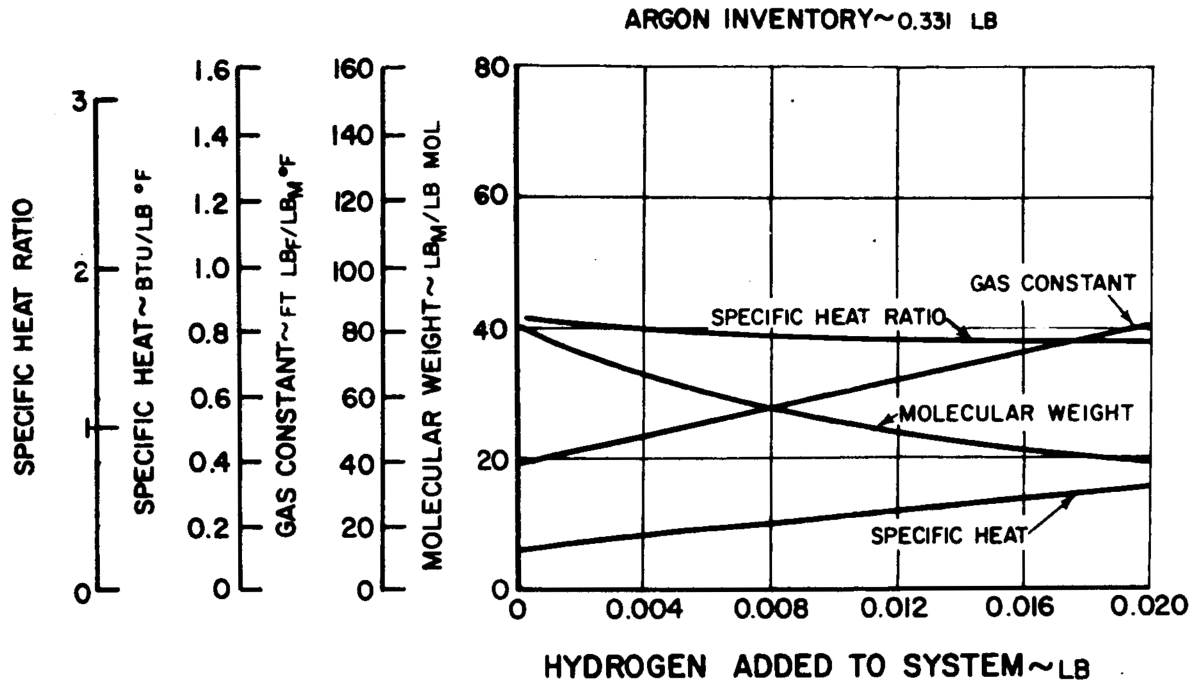


Figure 18 Effect of Hydrogen Addition on Working Fluid Properties

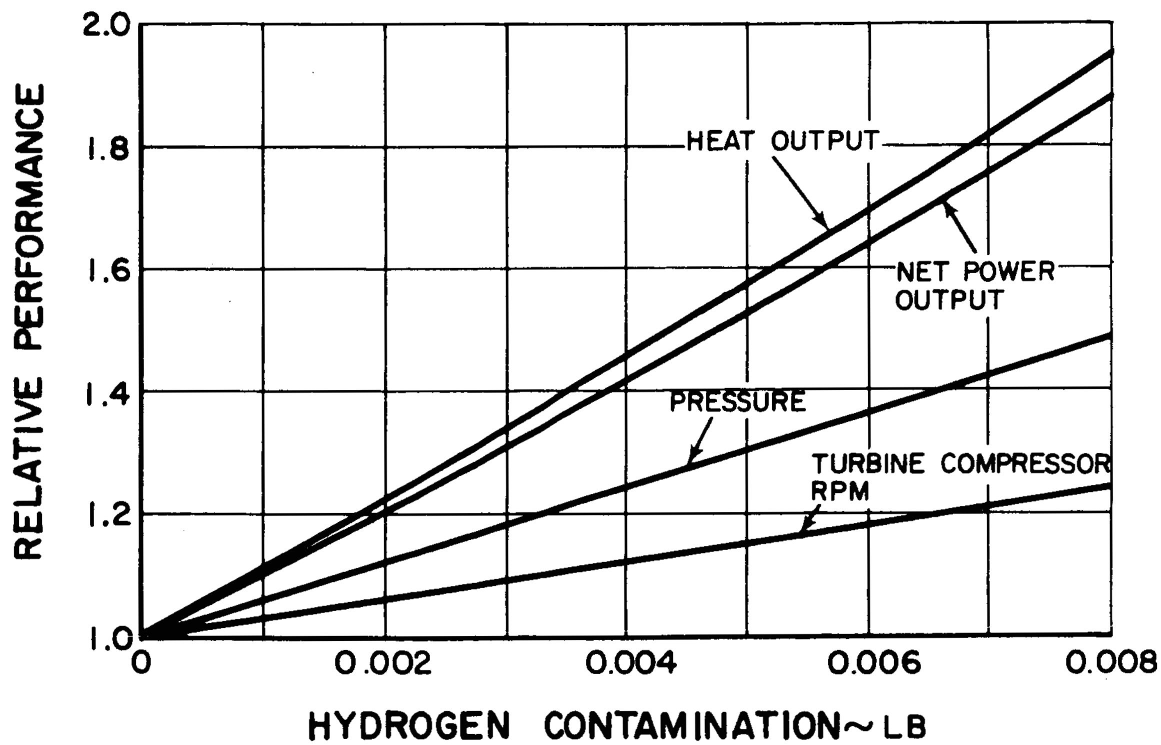


Figure 19 Effect of Hydrogen Addition on System Performance for Constant Turbine Inlet Temperature

In order to prevent exceeding the alternator rating, the Brayton-cycle system performance was evaluated allowing the turbine inlet temperature to vary so as to maintain constant net power output with hydrogen addition. The results of this study are presented in Figure 20. The turbine inlet temperature must be reduced to maintain constant power output. As a result the cycle efficiency is reduced and the required input thermal energy is increased. The system becomes non-selfsustaining with more than about 0.014 pound of hydrogen contamination. The turbine-compressor speed is reduced with increasing hydrogen contamination in this case.

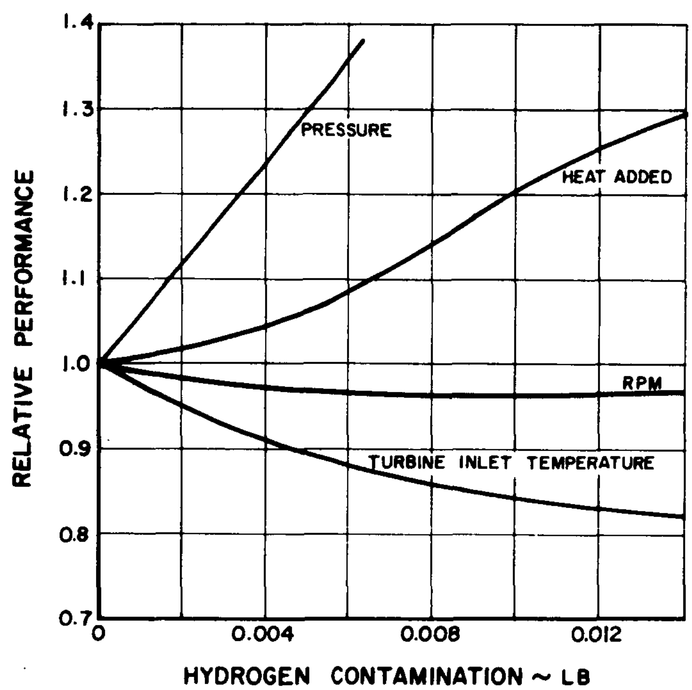


Figure 20 Effect of Hydrogen Addition on System Performance for Constant Net Power

One method of preventing the cycle power increase as hydrogen is admitted is to reduce the system pressure level with a pressure relief valve. If the net output power and the turbine inlet temperature were held constant, the compressor inlet pressure would vary as shown in Figure 21. The turbine-compressor rotor would run above design speed, reaching the limiting condition of 20 per cent overspeed with a contamination of 0.008 pound of hydrogen. At this condition

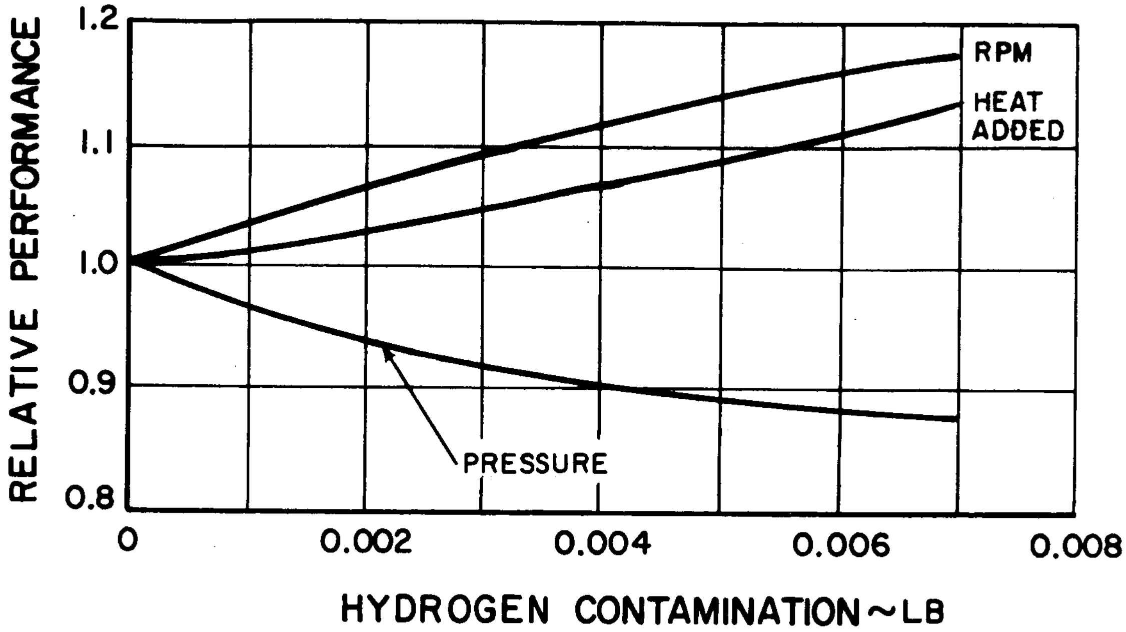


Figure 21 Effect of Hydrogen Addition on System Performance for Constant Net Power and Turbine Inlet Temperature

the heat source would have to supply approximately 15 per cent more thermal energy than at normal operating conditions.

The isotope heat source is often considered to be a constant energy source. The performance of the power system with constant heat input is presented in Figure 22 for various levels of hydrogen contamination. In this case no pressure relief was assumed, resulting in increasing pressure level with the hydrogen addition. The turbine inlet temperature decreases as a result of the increasing specific heat and increasing mass flow of the working fluid. As a result of the reduction in turbine inlet temperature, the power output decreases and the system becomes non-selfsustaining with about 0.008 pound of hydrogen contamination. If the pressure were not allowed to increase with hydrogen addition, but were held constant by a relief valve, and if the heat input were held constant, the system becomes non-selfsustaining with about 0.014 pound of hydrogen contamination. The results of this analysis are presented in Figure 23.

An isotope heat source will probably incorporate surplus material (fuel) to provide for control and the decay of the isotope. Therefore, some increase in heat input may be permissible. One case was examined where the pressure level was held constant by a pressure relief valve and the turbine inlet temperature varied to provide constant power output. The results are presented in Figure 24. In this case, the turbine-compressor speed exceeds 20 per cent overspeed with about 0.018 pound hydrogen contamination.

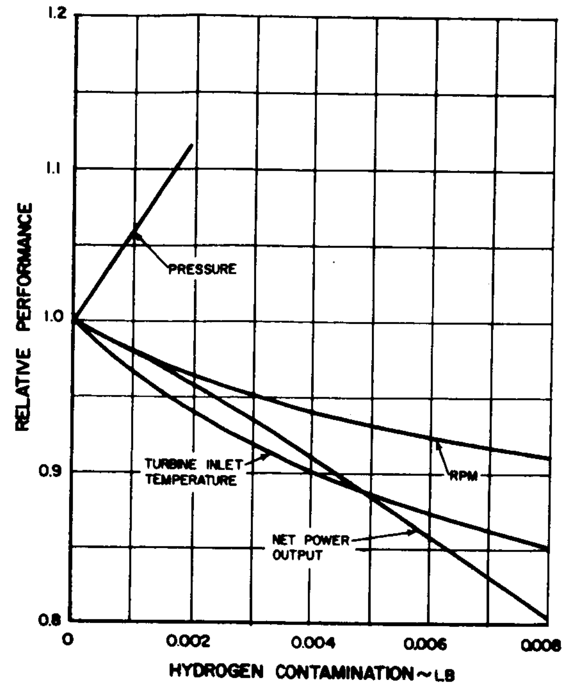


Figure 22 Effect of Hydrogen Addition on System Performance for Constant Heat Input

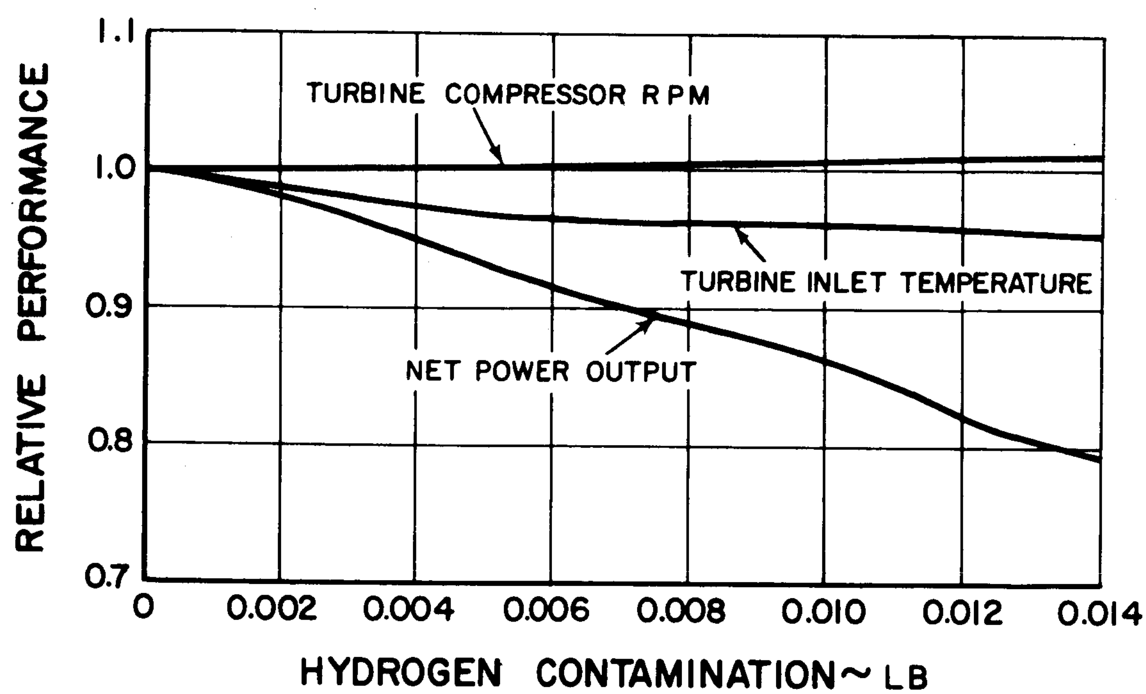


Figure 23 Effect of Hydrogen Addition on System Performance for Constant Heat Input and Pressure Level

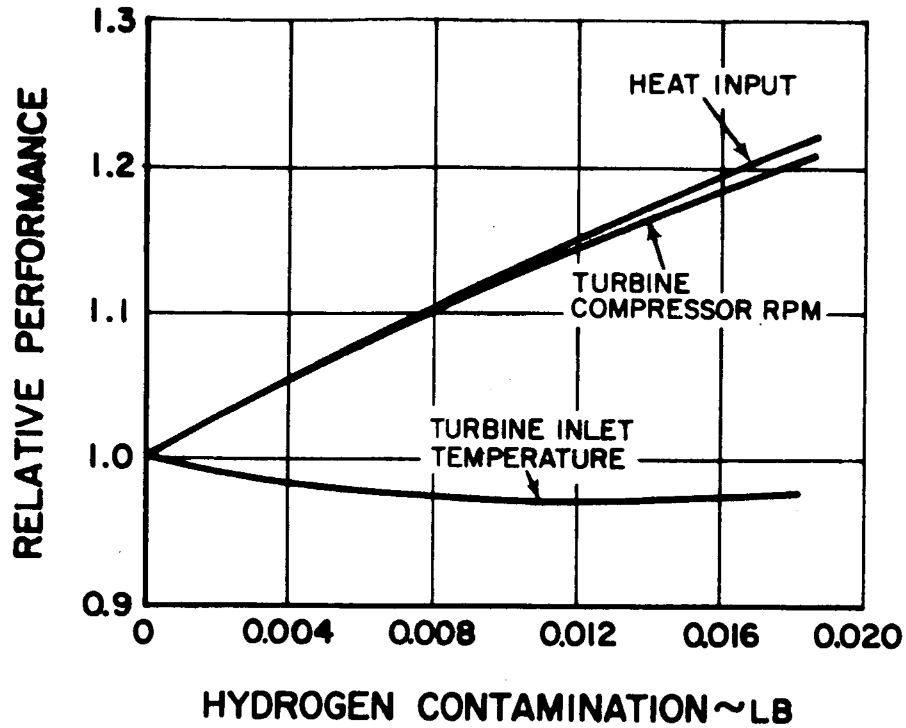


Figure 24 Effect of Hydrogen Addition on System Performance for Constant Net Power Output and Pressure Level

Since many of the cases studied involve an overspeed of the turbine-compressor, one case was examined in which the turbine-compressor speed and the net power output are held constant. Some pressure relief as well as control of the turbine inlet temperature are required. The results are presented in Figure 25. Because of the reduction in cycle efficiency due to the reduction in turbine inlet temperature, the heat source is required to supply more heat with hydrogen contamination. With 0.012 pound of hydrogen in the system the required heat input is increased 50 per cent.

The overall result of this study indicates that with some kind of control, either a pressure relief or heat source control (which controls turbine inlet temperature), contamination levels of 0.008 to 0.014 pound of hydrogen can be tolerated. Of course, this level of contamination is dependent on the inventory of argon assumed.

For this study a conservative (low) inventory of 0.331 pound of argon has been used. Inventories of 2 to 3 times this value may actually be involved in which the allowable contamination could be 2 to 3 times the values indicated. Since the selected polyphenyl ether oil contains 4.9 per cent of hydrogen, the allowable

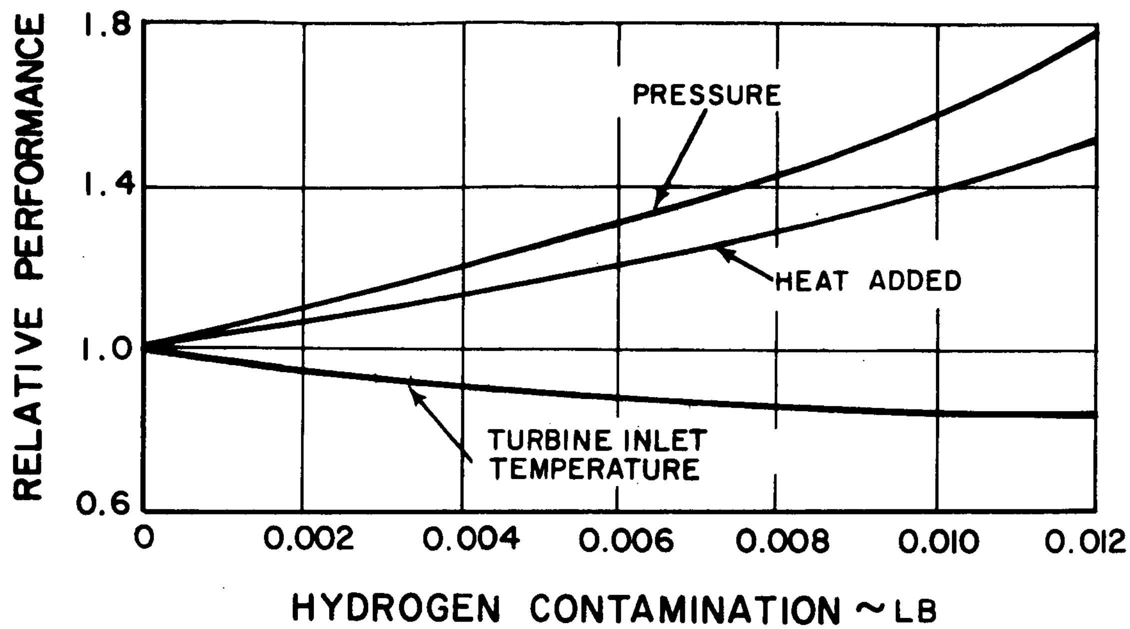


Figure 25 Effect of Hydrogen Addition on System Performance for Constant Net Power and Turbine-Compressor Speed

contamination of 0.008 to 0.014 pound of hydrogen represents 0.16 to 0.29 pound of oil (75 to 130 grams).

The hydrogen evolution will require some special consideration in the design of the Brayton-cycle powerplant. Perhaps the simplest approach is to provide a hydrogen window in the system to permit hydrogen to diffuse from the system while containing the cycle working fluid. For example, palladium can perform this function effectively. If such a window were employed, up to 5 pounds of oil can be accepted in the primary cycle fluid without seriously affecting the overall performance.

In normal operation only a small quantity of oil will be carried to the adsorber, since the bulk of the oil will be extracted from the argon in the centrifugal separator. The argon flow through the adsorber which is returned to the cycle is estimated to be 5.4 pounds per hour. If the separator operates as designed, 3 to 10 pounds of oil will be carried to the adsorber by the argon in the course of 10,000 hours. If the adsorber were to collect all but 1 to 2 per cent of the oil entering the cycle, contamination would be within the range established above as being the maximum acceptable without a hydrogen window. In the 600-hour adsorber test, 0.13 per cent of the oil entering passed through the adsorber, which corresponds to 2.2 per cent in 10,000 hours.

APPENDIX 1

References

APPENDIX 1
References

1. First Quarterly Progress Report, Brayton-Cycle Turbomachinery Rolling-Element Bearing System, NASA CR-54785, PWA-2713, October 1965

2. Second Quarterly Progress Report, Brayton-Cycle Turbomachinery Rolling-Element Bearing System, NASA CR-54915, PWA-2780, February 1966

3. Third Quarterly Progress Report, Brayton-Cycle Turbomachinery Rolling-Element Bearing System, NASA CR-54991, PWA-2845, May 1966

Distribution List
Contract NAS3-7635

To	No. of Copies
National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135	
Attention: B. Lubarsky, MS 500-201	1
I. Pinkel, MS 5-3	1
D. G. Beremand, MS 500-201	1
J. Heller, MS 500-201	1
W. Stewart, MS 5-9	1
D. C. Guentert, MS 500-201	1
J. E. Dilley, MS 500-309	1
W. J. Anderson, MS 6-1	1
Z. Nemeth, MS 6-1	1
E. Zaretsky, MS 49-1	1
R. L. Johnson, MS 5-8	1
L. P. Ludwig, MS 5-8	1
H. Rohlik, MS 6-1	1
B. Wong, MS 6-1	1
A. Straquadine, MS 500-203	1
E. Bisson, MS 5-3	1
L. Gertsma, MS 500-202	1
D. T. Bernatowicz, MS 500-201	1
T. A. Moss, MS 500-201	1
F. Dutee, MS 21-4	1
L. W. Ream, MS 500-201	1
Report Control, MS 5-5	1
Technology Utilization Office, MS 3-19	1
Librarian	1
National Aeronautics and Space Administration Washington, D. C. 20546	
Attention: T. C. Evans, MTF	1
F. P. Dixon, MTG	1
A. M. Andrus, ST	1
H. Rochen, RN	1
J. J. Lynch, RNP	1
National Aeronautics and Space Administration Scientific and Technical Information Facility P. O. Box 33, College Park, Maryland 20740	
Attention: Acquisitions Branch, SQT-34054	2+ repro
National Aeronautics and Space Administration Goddard Space Flight Center Greenbelt, Maryland 20771	
Attention: W. R. Cherry	1
Librarian	1
National Aeronautics and Space Administration Langley Research Center Langley Station, Hampton, Virginia 23365	
Attention: R. C. Wells	1
Librarian	1
National Aeronautics and Space Administration George C. Marshall Space Flight Center Huntsville, Alabama 35812	
Attention: E. Stuhlinger	1
Librarian	1
National Aeronautics and Space Administration Manned Spacecraft Center Houston, Texas 77058	
Attention: R. B. Ferguson	1
Librarian	1
National Aeronautics and Space Administration Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103	
Attention: J. W. Goldsmith	1
Librarian	1
National Aeronautics and Space Administration Ames Research Center Moffett Field, California 94035	
Attention: Librarian	1
Electronic Research Center 575 Technology Square Cambridge, Massachusetts, 02139	
Attention: Librarian	1

To:	No. of Copies
U.S. Atomic Energy Commission, DRD Washington, D.C. 20454	
Attention: N. Grossman	1
J. LaScalzo	1
R. Oehl	1
D. B. Hoatson, ARB	1
Librarian	1
U. S. Atomic Energy Commission Technical Information Extension P. O. Box 62, Oak Ridge, Tennessee 37831	
Attention: Librarian	1
U. S. Atomic Energy Commission Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois 60440	
Attention: Librarian	1
U. S. Army Engineer R&D Laboratories Gas Turbine Test Facility Fort Belvoir, Virginia 22060	
Attention: W. Crim	1
Department of the Navy Office of Naval Research Washington, D. C. 20360	
Attention: Dr. R. Roberts	1
Department of the Navy Bureau of Naval Weapons Washington 25, D.C.	
Attention: Code RAPP	1
Department of the Navy Bureau of Ships Washington 25, D. C.	
Attention: G. L. Graves	1
Department of the Navy Naval Research Laboratory Washington, D. C. 20390	
Attention: Librarian	1
Air Force Systems Command Aeronautical Systems Division Wright-Patterson AFB, Ohio 45433	
Attention: G. W. Sherman, APIP	1
Librarian	1
Air Force Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433	
Attention: John L. Morris, APFL	1
National Bureau of Standards Washington 25, D. C.	
Attention: Librarian	1
Massachusetts Institute of Technology Cambridge, Massachusetts 02139	
Attention: Librarian	1
University of Pennsylvania Power Information Center, Moore School Building 200 South 33rd Street Philadelphia, Pennsulvania 19104	1
Battelle-Northwest P. O. Box 999, Richland, Washington 99352	
Attention: Librarian	1
Institute for Defense Analyses 400 Army Navy Drive Arlington, Virginia 22202	
Attention: Librarian	1
The Franklin Institute Benjamin Franklin Parkway at 20th Street Philadelphia, Pennsylvania 19103	
Attention: Librarian	1

To:	No. of Copies
The Rand Corporation 1700 Main Street Santa Monica, California Attention: Librarian	1
Williams Research Walled Lake, Michigan Attention: Librarian	1
Aerojet-General Coporation Azusa, California 91703 Attention: Librarian	1
Aerojet-General Nucleonics San Ramon, California 94583 Attention: Librarian	1
AiResearch Manufacturing Company A Division of the Garrett Corporation Phoenix, Arizona 85034 Attention: Librarian	1
AiResearch Manufacturing Company A Division of the Garrett Corporation 9851 Sepulveda Boulevard Los Angeles, California 90009 Attention: Librarian	1
Avco Rand Corporation 201 Lowell Street Wilmington, Massachusetts Attention: Librarian	1
Barden Corporation Danbury, Connecticut 06810 Attention: Technical Library	1
Chrysler Corporation Space Division, Technical Information Center P. O. Box 26018, New Orleans, Louisiana 70126 Attention: Librarian	1
Douglas Aircraft Company 3000 Ocean Park Boulevard Santa Monica, California Attention: Librarian	1
Electro-Optical Systems, Inc. 300 North Halstead Avenue Pasadena, California 91107 Attention: Librarian	1
Fairchild Hiller Republic Aviation Division Farmingdale, Long Island, New York 11735 Attention: Librarian	1
General Dynamics Corporation General Atomic Division San Diego, California Attention: Librarian 92112	1
General Electric Company Flight Propulsion Laboratory Department Cincinnati, Ohio 45215 Attention: Librarian	1
General Electric Company Lynn, Massachusetts Attention: Librarian	1
General Electric Company Missile and Space Vehicle Department 3198 Chestnut Street Philadelphia, Pennsylvania 19104 Attention: Librarian	1
Lockheed Aircraft Corporation Missiles & Space Division P. O. Box 504, Sunnyvale, California Attention: Librarian	1
Martin Company, Baltimore Division Martin-Marietta Corporation P. O. Box 5042, Baltimore, Maryland 21203 Attention: Librarian	1
Mechanical Technology Incorporated 968 Albany-Shaker Road Latham, New York 12110 Attention: Librarian	1
North American Aviation, Inc. Atomics International Division 8900 DeSoto Avenue Canoga Park, California Attention: Librarian	1
North American Aviation, Inc. Space and Information Systems Division Downey, California 90241 Attention: Librarian	1
Philco Corporation, Aeronutronic Division Ford Road, Newport Beach, California 92663 Attention: Librarian	1
Solar 2200 Pacific Highway San Diego, California 92112 Attention: Librarian	1
Space General Corporation 9200 East Flair Drive El Monte, California Attention: Librarian	1
Space Technology Laboratories, Inc. One Space Park Redondo Beach, California Attention: Librarian	1
*Sunstrand Aviation 2480 West 70th Avenue Denver, Colorado 80221 Attention: Librarian	1
S. V. Manson & Company, Inc. 2420 Wilson Boulevard Arlington, Virginia 22201 Attention: Librarian	1
The Bendix Corporation Research Laboratories Division Southfield, Michigan Attention: Librarian	1
The Boeing Company Aero-Space Division P. O. Box 307, Seattle 25, Washington Attention: Librarian	1
TRW, Inc. 7209 Platt Avenue Cleveland, Ohio 44104 Attention: Librarian	1
Union Carbide Corporation Linde Division 61 East Park Drive, Tonowanda, New York Attention: Librarian	1
United Aircraft Corporation Research Laboratories East Hartford, Connecticut 06108 Attention: Librarian	1
Westinghouse Electric Corporation Astronuclear Laboratory P. O. Box 10864 Pittsburgh, Pennsylvania 15236 Attention: Librarian	1